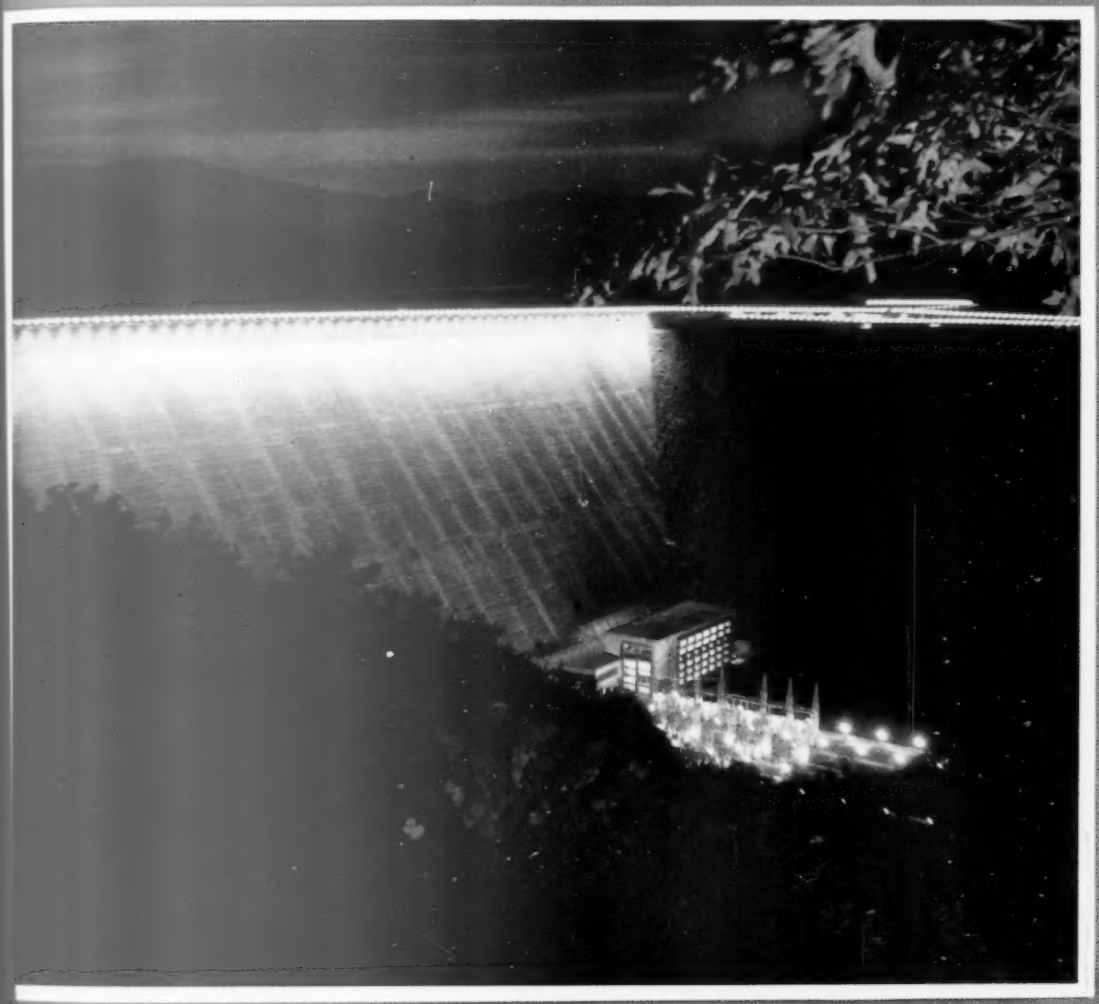
ALLIS-CHALMERS Electrical REVIEW

1ST QUARTER 1952



HOW MUCH CAN A BREAKER TAKE?... Page 4

ALLIS-CHALMERS

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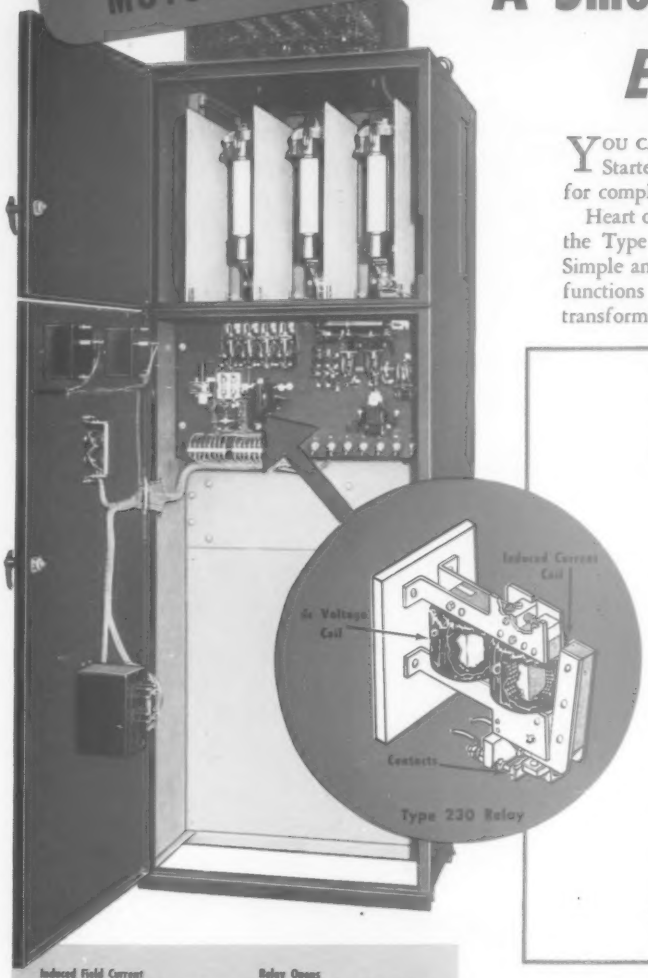
Dependable..

A Smooth, Accurate Start *EVERY TIME!*

YOU CAN DEPEND on Allis-Chalmers Synchronous Motor Starters for accurate and consistent field application . . . for complete line-to-load protection.

Heart of the Allis-Chalmers Synchronous Motor Starter is the Type 230 polarized field-frequency application relay. Simple and dependable, this single relay performs all these functions without the use of primary potential or current transformers:



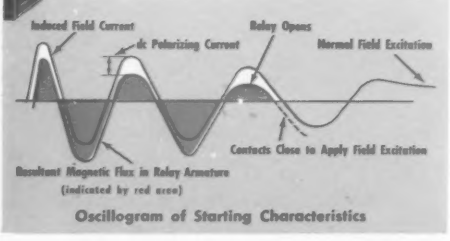
★ **Applies dc excitation automatically when proper rotor speed is reached.**

★ **Selects exact half cycle and the most favorable angle between rotating field and revolving magnetic stator field to apply excitation.**

★ **If motor pulls out of step, it removes field excitation promptly at instant of pull-out.**

★ **Resynchronizes automatically after pull-out if condition has been corrected.**

THIS IS HOW THE RELAY WORKS. The transformer action between the stator and the rotor of a synchronous motor (during acceleration) causes an alternating current to be induced in the field circuit of the rotor. A decrease in the magnitude and frequency of the induced rotor current as the motor accelerates, together with a biasing voltage from the excitation source, causes the Type 230 field application relay to apply field excitation at the most favorable point of stator-rotor relationship. The relay will maintain the field excitation during normal motor operation, but will operate to remove the excitation on motor pull-out. The relay will resynchronize the motor if the pull-out condition has been removed before protective devices operate to disconnect the motor from the line.



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ALLIS-CHALMERS

There is an Allis-Chalmers Starter for Every Motor Need

ALLIS-CHALMERS

Electrical REVIEW

THE COVER

FONTANA AT NIGHT belies its work-a-day lot as man's servant. Hydroelectric power from its giant turbines is distributed to light the homes and drive the industrial wheels of the Great Smoky Mountain area. The two hydraulic turbines originally installed will soon be augmented with a third 91,500-hp, 150-rpm, 330-ft head hydraulic turbine now under construction.

A-C Staff Photo

CONTENTS

How Much Can a Breaker Take? 4
P. L. TAYLOR

Pull-Out Reserve — Controlled and Indicated 11
T. B. MONTGOMERY and D. V. HOTSON

PT's Are Getting Smaller 20
D. R. LAIB

Safeguarding Large AC Motors 24
E. N. GIGOT and F. C. OSTERLAND

Analogies and Energies 30
D. JOURNEAUX

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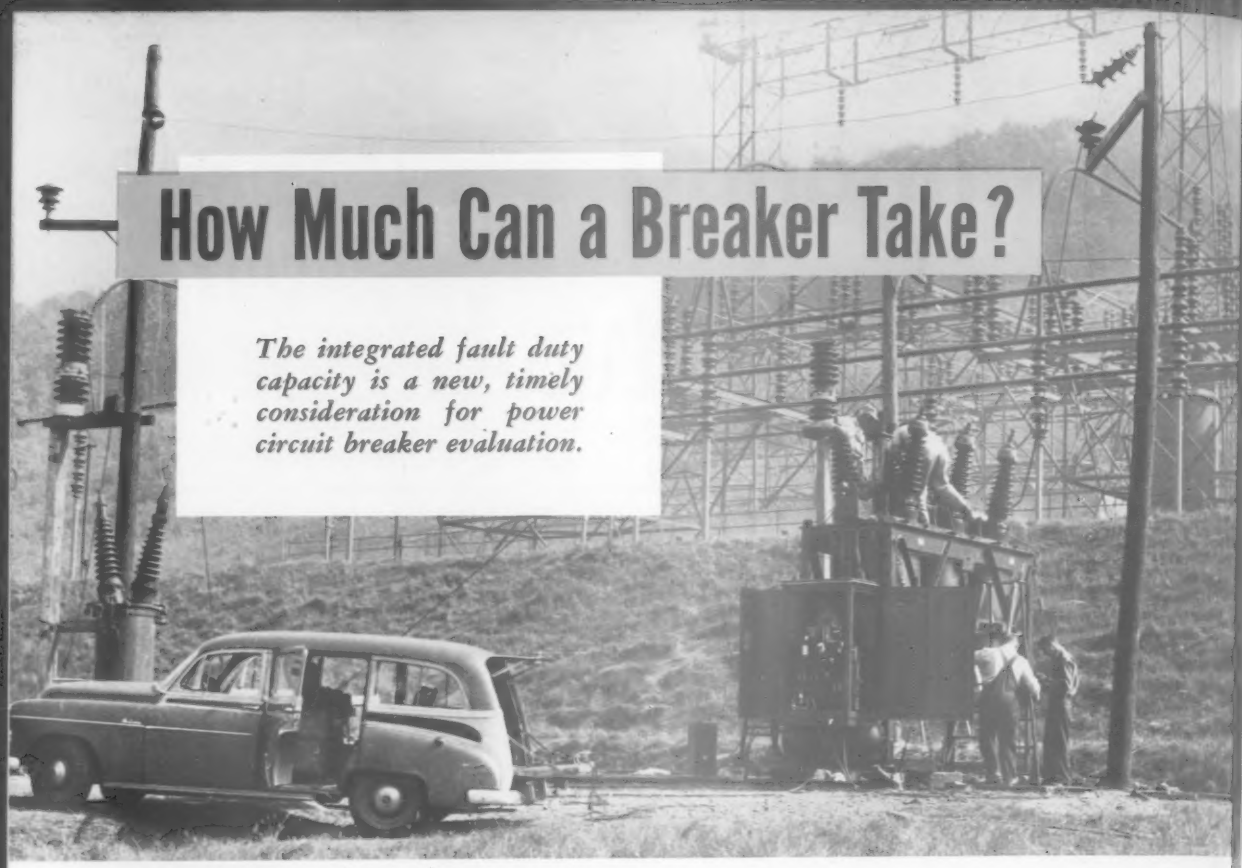
How Much Can a Breaker Take?

The integrated fault duty capacity is a new, timely consideration for power circuit breaker evaluation.



TEST BREAKER SETUP in the 66-kv yard shows the 230-kv yard in the background and the insulation test car in front of the test breaker. The potential transformer and one of two capacitance dividers are shown at left. Second divider is pole mounted in back of the breaker. **(FIGURE 1)**

by P. L. TAYLOR*
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Allis-Chalmers Mfg. Co.
Boston, Mass.

THE SAFE PERMISSIBLE accumulated fault-interrupting duty between maintenance periods is an important yardstick of circuit breaker performance. A current technical paper[1] suggests as a desirable integrated-fault duty capacity, a value of ten times the interrupting rating of the breaker, with at least three interruptions at rated interrupting capacity.

Recent field tests made on a standard 69-kv, 1500-mva oil circuit breaker at the Siegfried substation of the Pennsylvania Power and Light Company are of particular interest in this respect, because they included fault tests which constituted an accumulated interrupting duty (without maintenance or adjustment) of approximately 18 times the interrupting rating of the breaker. Eleven of the interruptions were made at or beyond rated interrupting capacity.

This fault test series is believed to constitute the highest integrated-fault duty to which a breaker of this class has ever been subjected.

The breaker, which is equipped with single-break *Turbo-Ruptor* interrupting devices and operates with relatively moderate contact speeds, was also subjected to a number of line charging and discharging tests at line lengths up to 100 miles with all three-phase wires connected in parallel to increase the duty. In all cases it cleared without restriking.

Standard breaker tested

The test breaker, shown in Figure 1 on field test location, was a standard frame-mounted, tank type oil breaker diverted from a production order after routine operation and speedgraph[2] checks.

This breaker was equipped with a standard, fully mechanically trip-free pneumatic operating mechanism. Shown in Figure 2, this mechanism is designed to trip free mechanically on every opening operation whether the duty is "O," "CO," or "OC." It is recoupled after such trip-free operations sufficiently fast to permit instantane-

* The author wishes to express his appreciation to the Pennsylvania Power & Light Company for making their system available for these tests, and to their engineers and operating and test personnel, who so ably arranged and conducted these tests.

He also wishes to thank J. J. Borek and W. S. Lorenz, Allis-Chalmers Mfg. Co., for their fine work on the special instrumentation.

[1] *Consideration in Testing, Rating, and Application of Power Circuit Breakers,* Evans, Byron and Kilgore, *AIEE* Paper No. 52-11.

[2] *The Speedgraph,* Taylor, P. L., Allis-Chalmers *Electrical Review,* March, 1937.

ous reclosures in substantially less than 20 cycles. Pneumatic operators of this type have been in service for over ten years.[3]

The pole unit mechanisms provide straight-line contact motion and are housed in sealed wells with removable inspection and adjustment covers. A removable hood in turn encloses each sealed mechanism well. The hood also covers the operating crank and horizontal connecting rod compartment on one side, and the bushing current transformer lead compartment on the other side. Figure 3 shows the general arrangement of the pole unit and its mechanism.

The interrupting device was originally developed for five-cycle, base-mounted breakers 115 kv and above. More recently it has been adapted to breakers of the 69-kv class and below. A section view of the interrupting device used on these tests is shown in Figure 4. This interrupting device is notable for its structural simplicity, including its single-break bayonet and tulip type multiple steep-angle wedge contacts. Since single-break contacts are used, the interrupting section of the interrupting device could be made readily removable as a unit, leaving the contacts in operating position and fully accessible for observation and adjustment.

The interrupting or shell group of the interrupting device consists essentially of a shell, housing a pressure generating chamber immediately below the stationary contacts, and a throat of arc-resisting disc laminations. These laminations are cut out to form a central bayonet contact passage, and two oppositely disposed, tapered helical oil passages enveloping and connecting with it. Vent passages from the central contact passages to the tank space are provided at spaced intervals.

The pressure generated in the upper chamber as the arc is drawn acts upon the upper ends of the two helical oil passages, to force oil and relatively un-ionized gas to flow rapidly in intimate contact with the developing arc stream. This rapid flow creates an intensely turbulent swirling and sweeping action, which effectively de-ionizes the arc space, and achieves interruption at an early current zero.

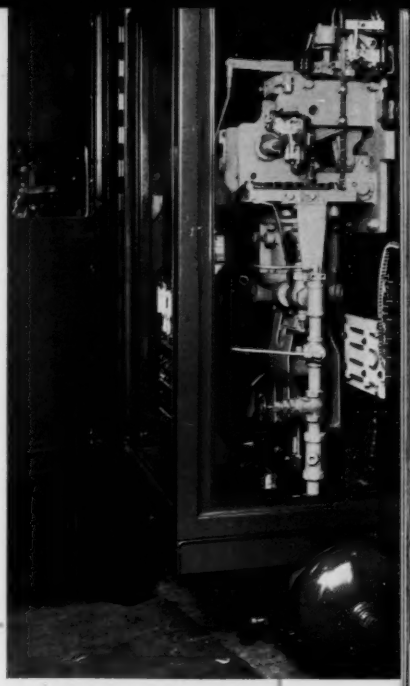
Field test setup

These field tests were made at the Siegfried substation of the Pennsylvania Power and Light Company, which is the center of the 66-kv transmission network of that system. Figure 5 is a one-line diagram of the 66-kv and 230-kv yards at Siegfried. Also shown are the temporary test connections for the short-circuit test in the 66-kv upper yard.

Figure 1 shows the test setup in progress with the 230-kv yard in the background and insulation test car in front of the breaker. At the left is a potential transformer and one of the two capacitance dividers mounted on a temporary pole. The second capacitance divider is mounted on a second temporary pole immediately behind the breaker, which is bolted to a transformer track.

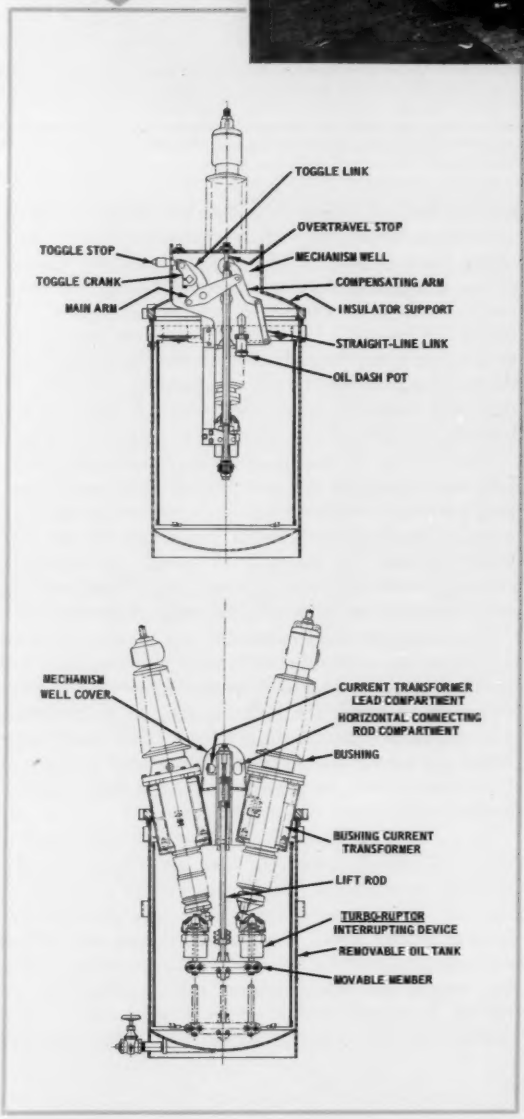
As indicated in Figure 5, all tests were made using the Freemansburg No. 2 line. From previous tests at this

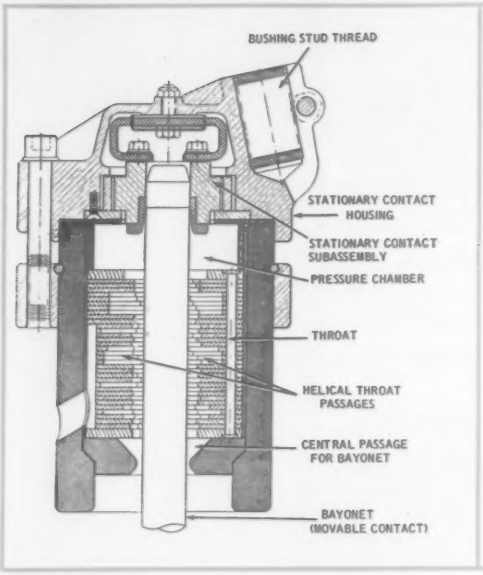
[3] *High Speed Reclosing Through the Years,* Ashenden, H. B., Allis-Chalmers *Electrical Review,* Third Quarter, 1949.



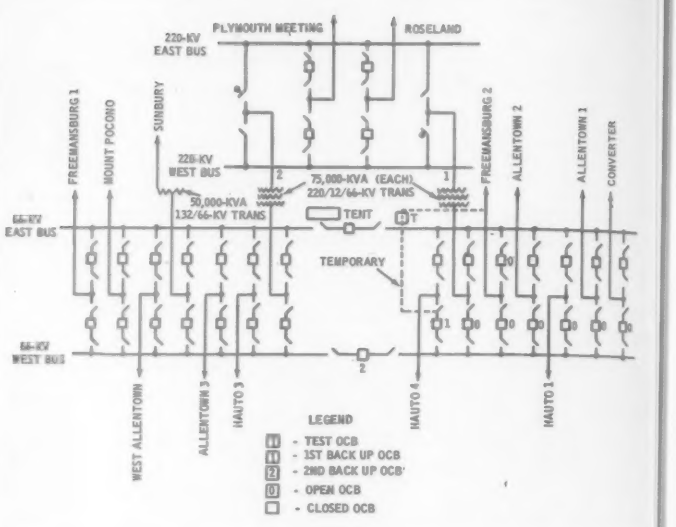
LEFT SIDE view of mechanically trip-free pneumatic operator shows the arrangement of the pneumatic system and storage tank mounted below the cabinet. The control panel is directly accessible from the front. **(FIG. 2)**

SECTION VIEW of breaker pole unit used in test shows the pole unit mechanism which provides a straight-line contact motion. **(FIGURE 3)**





CUTAWAY VIEW of a complete 69-kv, 1500-mva Turbo-Ruptor interrupting device shows the bayonet in closed position, engaging multiple steep-angle wedge tulip type stationary contacts. These have separate arcing and current carrying areas. **(FIG. 4)**



STATION BUS arrangement and temporary test connections for the 69-kv breaker field tests with breaker connected to Freemansburg No. 2 line are shown diagrammatically. Tent for recording instruments is shown between the two 75,000-kva transformer banks which supplied the major portion of the fault power for the breaker tests. **(FIG. 5)**

location, and calculations to include the effects of capacity added to the system, the various required fault duties were closely predetermined. The lowest fault current was obtained by applying a ground at Freemansburg, and intermediate values by grounds at intermediate points. To obtain the maximum fault values the ground was applied at the first tower immediately outside the station yard. All recording instruments and the directing center for the tests were located in a tent about 100 feet from the test breaker, as indicated on the one-line diagram.

Since the test breaker required no maintenance or adjustment throughout the test program, the power company's carefully coordinated program of test arrangements — including the making of all test setups on one line, which obviated the necessity of system and generator switching — resulted in an unusually expeditious handling and completion of the entire test program in one night.

After setup on test location the test breaker operation was rechecked with a circuit breaker speed analyzer and its adjustments were found to be satisfactory. No attempt was made to reduce the reclosing time to its minimum practical value. The speedgraph chart taken immediately before the breaker was shipped is reproduced in Figure 6. Power factor tests were made and oil samples taken at intervals throughout the test program.

Magnetic and cathode-ray oscillographs were used to obtain the records of the tests. The magnetic oscillographs recorded the three bus voltages, bus voltage to ground on the faulted phase, voltage across the breaker, fault current, breaker contact travel, trip current, closing coil voltage and tank pressure. On the line switching tests, line charging current and line-to-ground voltages were also recorded. A portable cathode-ray oscillograph was set up to measure the line-to-ground voltage on the line switching tests, and voltage across the breaker on the fault tests. Figure 7 shows the portable cathode-ray oscillograph with special high-speed rotating drum camera used on these tests.

The capacitance dividers shown in Figure 1 were located one on each side of the test breaker and connected line and bus to ground to provide accurate low-drain sources of measuring voltage for both the magnetic and cathode-ray oscillograph. Proper output voltages were obtained by loading the low side of the dividers with oil-filled paper capacitors shunted by mica capacitors. The output voltage was then conducted to the instrument location through coaxial cables, and there additional loading was applied to properly balance the two voltages so that their difference could be used to indicate the voltage across the breaker.

Amplifier for magnetic oscillograph

An unusual feature of the instrumentation was the amplifier (shown below the cathode-ray oscillograph in Figure 7) used for the first time on this test to operate magnetic oscillograph galvanometers from the capacitance divider voltages.

It is a three-channel, three-stage, direct-coupled, push-pull dc amplifier with a cathode-follower type output to the galvanometer. Operating power is supplied either from a 115-volt ac circuit, or by a 12-volt storage battery supply through a small inverter set. The latter is usually advantageous even when 115 volts ac is available, especially on field tests, to avoid either fluctuation of supply voltage or interaction between power supply and test circuit grounds under fault test conditions.

The three channels may be used for any three voltages as long as they have a common reference ground. They may, for example, be used for two voltages and a differ-

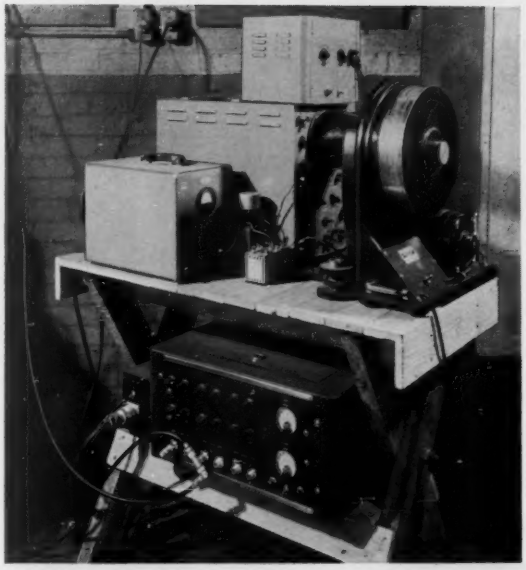
ential voltage, such as the two line-to-ground voltages on either side of a breaker under test and the differential between the two, which is the voltage across the breaker.

Frequency response exceeds that of magnetic oscillograph galvanometers, being flat from zero to over 10 kilocycles at full gain, so as to faithfully reproduce the input wave under all anticipated conditions, including sustained voltages such as are encountered in line dropping tests.

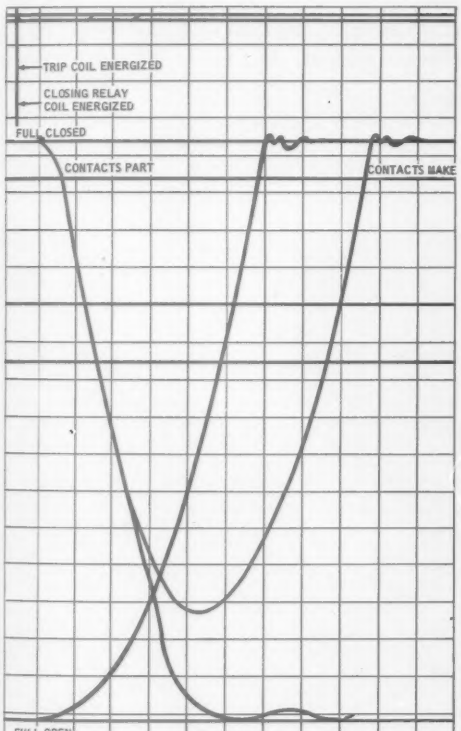
Test results impressive

A total of 28 interruptions were included in the fault test series, which was completed within an eight-hour period. The fault currents ranged from 1460 amperes to 13,620 amperes, or from 173 mva to 1580 mva on a three-phase basis. Various duty cycles were performed, including instantaneous reclosures and four-shot duty cycles with the first reclosure instantaneous.

The last 11 fault interruptions were made at the maximum available short-circuit capacity of the system. The last four interruptions were at maximum capacity on an "O" + inst. "CO" + 60-sec + "CO" + 60-sec + "CO" duty cycle. Taking into account the rating factor for this duty cycle, these last four shots were made at an average of 116 percent of breaker rating.



PORTABLE CATHODE-RAY oscillograph (top) with special high-speed rotating drum filmholder provided the exceptionally high writing speeds for recording recovery voltages. A special three-channel amplifier (bottom) provided for accurate magnetic oscillograph recording of transient and sustained voltages on disconnected lines. **(FIG. 7)**



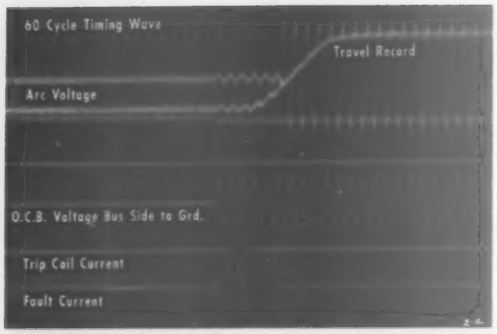
TIME TRAVEL CHART shows open, close, and open-close operations of the test breaker on routine factory test. On instantaneous reclosing operation shown on chart the mechanism tripped free, recoupled, allowed contacts to open to over 12 inches of stroke and completed a reclosure in 18¼ cycles. **(FIGURE 6)**

TABLE I

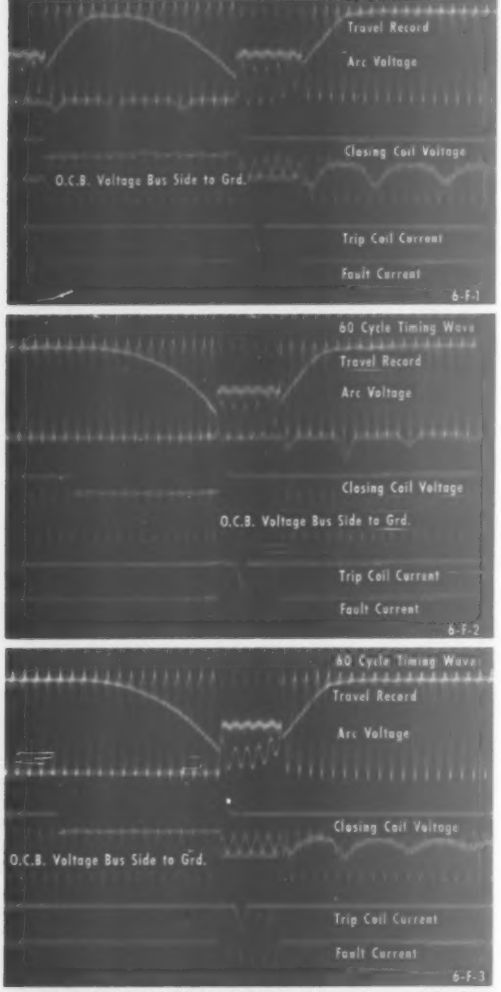
INTERRUPTING TEST DATA

Test No.	Duty	R.M.S. Amps.	Kv to Neut.	Equiv. 3 Phase Mva	Inter. Time Cycles
2a	O	1490	39.6	177	4.27
2b	CO	1460	39.5	173	4.65
3a	O	3196	39.1	376	4.52
3b-1	CO+	3254	38.5	375	4.55
3b-2	15 sec.+CO	3290	38.9	384	4.87
3c-1	CO+	3100	37.4	348	4.73
3c-2	40 cyc.+CO	3191	38.2	366	4.60
4a	O	5830	37.8	661	4.29
4b	O+	5850	38.0	667	4.25
	inst. CO	5870	38.0	668	4.45
4c	O+	5980	37.9	680	4.18
	inst. CO	5850	37.5	659	4.87
5a	O	9200	37.8	1043	3.48
5c-1	CO+	9450	37.5	1061	4.13
5c-2	15 sec.+CO	9200	38.6	1065	4.55
5d	O+	9270	38.2	1061	3.94
	inst. CO	9380	37.1	1043	4.20
6a	O	13420	37.4	1504	3.25
6b-1	CO+	13620	38.2	1561	4.05
6b-2	15 sec.+CO	13540	38.4	1560	3.79
6c	OC	13330	39.5	1580	4.09
6d	OC	12450	38.7	1441	4.00
6e-1	CO+	12300	39.6	1462	3.69
6e-2	2 sec. +CO	12760	39.8	1521	4.11
6f-1*	O+	12780	39.9	1526	3.68
	inst. CO+	12980	37.9	1475	4.00
6f-2*	60 sec.+CO+	12750	39.8	1520	4.00
6f-3*	60 sec.+CO	13260	39.5	1570	3.67
	Total accumulated	238,071		26,487	

* Taking into account the rating factor for this duty cycle, these last four shots average to be at 116 percent of breaker rating for three-phase application.



MAGNETIC OSCILLOGRAM shows the interrupting performance on the first fault test which was an "O" operation at 1490 amperes or 11 percent rating. A high capacity test is shown below. **(FIG. 8a)**



THREE MAGNETIC OSCILLOGRAMS show in sequence the four interruptions made on an O-instantaneous CO-60 cycles-CO-60 cycles-CO duty cycle at 116 percent rating. **(FIGURE 8b)**

The accumulated fault interruption for this test series was 26,487,000 kva, 3-phase equivalent. The accumulated fault amperes interrupted on the single pole was 238,071.

Table I shows a complete tabulation of these tests. All interrupting times were less than five cycles, including those after instantaneous reclosure. The breaker handled all capacities and duty cycles easily. Since it is rather freely vented, vapor was expelled quite freely on the heavier shots, showing clearly in the cold night air, but no oil was thrown.

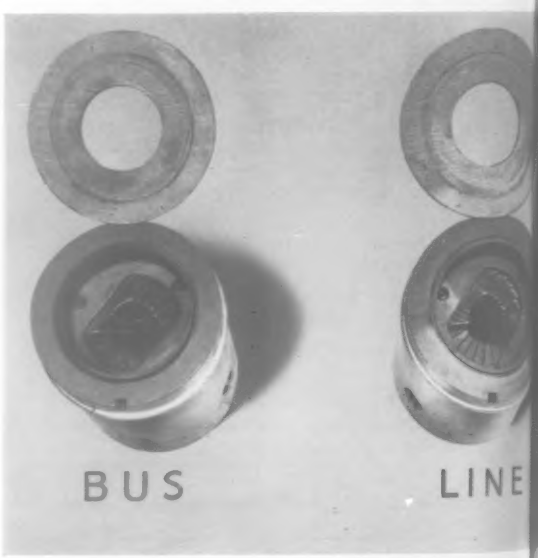
After being subjected to this unusually high integrated-fault duty test series the original oil still tested 18.5 kv in a standard test cup. It had, of course, become dark with finely divided carbon which had not had opportunity to settle out, and indicated need of reconditioning.

Typical oscillograms of Test 2a, which was an "O" operation at 11 percent capacity, and of Test 6f-1, 6f-2, 6f-3, which was an "O" + inst. "CO" + 60-sec + "CO" + 60-sec + "CO" at 116-percent capacity, are shown in Figure 8.

Figure 9 shows the upper portion of the interrupting device shell groups after completion of the tests. The throats were only slightly and smoothly eroded.

Figure 10 shows the used bayonet and tulip contacts in comparison with new ones. Figure 11 is a closer view with the used tulip contacts disassembled to show the flat contact area still essentially unmarked except for slight mechanical rubbing. In spite of the high accumulated duty, considerable additional service would be expected from these contacts.

A few hours previous to the fault tests, a series of line charging and discharging tests were made on 50 and 100



***TURBO-RUPTOR* SHELL GROUPS** are shown after completion of all tests shown in Tables I and II, looking down through the pressure generating chambers into the throats. Upper throat laminations used in tests show only limited smooth erosion. **(FIGURE 9)**

miles of line, in each case with all three-phase wires in parallel to increase the charging current. A tabulation of the results is shown in Table II. No restrikes were experienced on any test, and reignitions occurred only on the last test with 100 miles of three-conductor wires in parallel. The interrupting time on this test was 3.6 cycles and the maximum voltage was 144 percent of normal peak voltage. The maximum interrupting time on the balance of the line discharging tests was 2.87 cycles.

Breakers progress with load growth

The accumulated fault-interrupting duty without maintenance on these tests was nearly 18 times the interrupting rating of the breaker, or some 240,000 amperes, and included 11 interruptions at or slightly over the breaker rating. This integrated duty, as well as the number of full-rated capacity interruptions included in it, were considerably in excess of the proposed value and also of those on any previously reported tests on a breaker of this class.

In using values, or factors for evaluating the integrated-fault duty capacity, the operating engineer will undoubtedly prefer an evaluation in terms of kva, whereas the breaker designer will usually find the value of accumulated amperes to be the more significant. Arc energy is one of the major factors in determining the permissible integrated duty for this class of breaker, and in general the current is more indicative of the arc energy in a particular breaker design than is the kva interrupted.

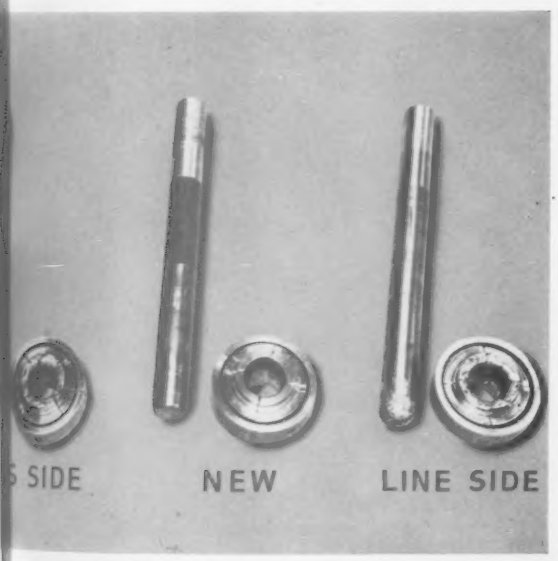
For example, it does not necessarily follow from these test results that a higher interrupting capacity breaker of this type and voltage class, or a lower voltage breaker of the same kva interrupting rating, is at present suitable for an accumulated duty of 15 to 20 times its rating without maintenance. On the other hand, the demonstrated integrated-current capacity, translated into kva for a higher voltage breaker with similar characteristics, may well be indicative of the feasibility of using an integrated-duty capacity factor of the order of 15 to 20 times the interrupting rating for that breaker.

Exhaustive field test series, such as that reported here, demonstrate that improvements in tank type oil circuit breakers and interrupting devices can be expected to keep pace with system growth and the resulting operating requirements, including those for substantial integrated-duty capacity.

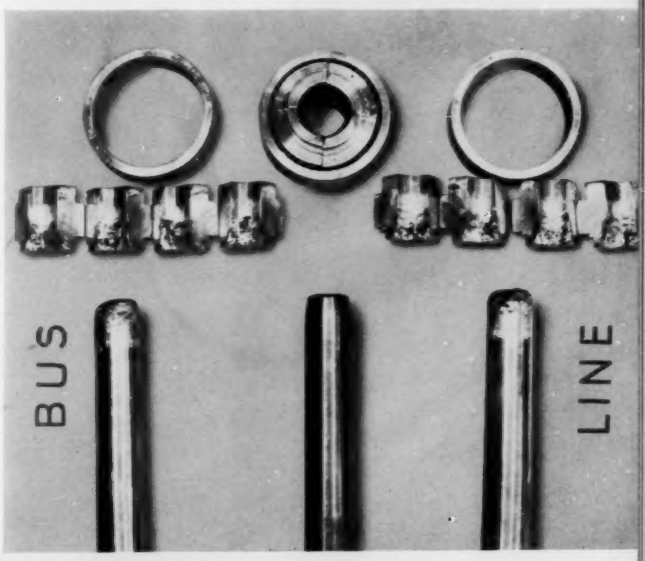
TABLE II

LINE SWITCHING TESTS					
Test No.	Duty	R.M.S. Amps.	Int. Time Cycles	Max. Volts % Normal Peak	Miles of Line
1a-1	C	14	——	——	50-3 wires
1a-2	O	14	2.65	100	50-3 wires
1a-3	O	14	No record	——	50-3 wires
1b-1	C	19.6	——	——	100-3 wires
1b-2	O	19.6	2.65	100	100-3 wires
1b-3	C	19.6	——	——	100-3 wires
1b-4	O	19.6	2.65	100	100-3 wires
1b-5	O	19.6	2.63	100	100-3 wires
1b-6	C	19.6	——	——	100-3 wires
1b-7	O	19.6	2.87	100	100-3 wires
1b-8	O	19.6	*3.58	144	100-3 wires

* Reignitions on this test only. Time shown is final interruption. No restrikes on any test.



USED AND UNUSED bayonet and tulip contacts were compared after the tests to demonstrate the durability of the contacts on this extended test series. Used contacts (at either end) show relatively little wear when compared to unused contacts (center). **(FIGURE 10)**

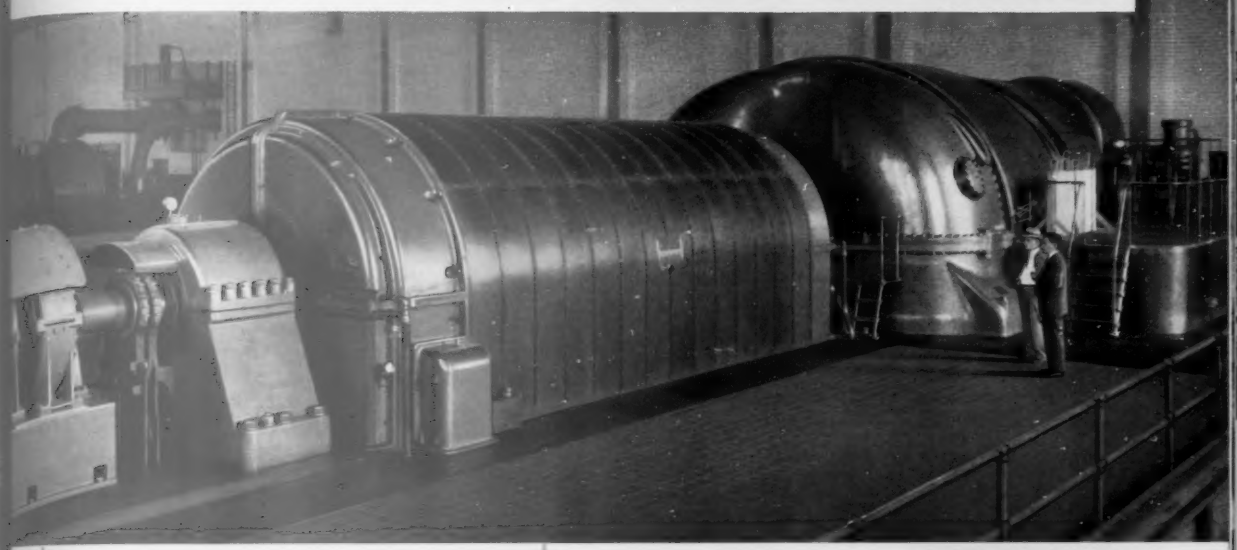


TULIP CONTACT GROUPS used in tests were disassembled to show unmarked contact area remaining on the vertical inside surface of the tulip segments. Burning was confined to arcing area. Contacts are suitable for considerable additional interrupting duty. **(FIGURE 11)**

INLET SECTION for a 57,500-hp, 112-ft head, 85.7-rpm vertical Francis runner, plate steel spiral casing turbine is being assembled for the second of eight similar units being built for the Fort Randall River project on the Missouri River. Because of their size, sections are shipped to the site for riveting in the field. Spoke supports provide temporary bracing during shop construction and are removed prior to shipment. The total shipping weight of the complete spiral casing and stay ring assembly will approximate a half-million pounds.

A-C Staff

PULL-OUT RESERVE—Controlled and Indicated



Greater generator stability is now provided by modern control even for low short circuit ratio machines which have been in operation for many years.

by **T. B. MONTGOMERY**
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Control Section
and
D. V. HOTSON
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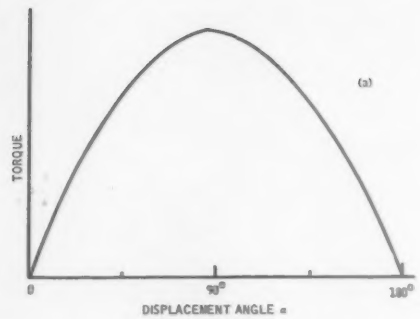
A GENERATOR SHORT-CIRCUIT ratio of 0.9 was general practice a decade ago. Now ratios average 0.8 and the trend is to even lower ratios for future units. Modern voltage regulators are a prime factor in this trend and are being recognized as an integral part of generator operating characteristics.

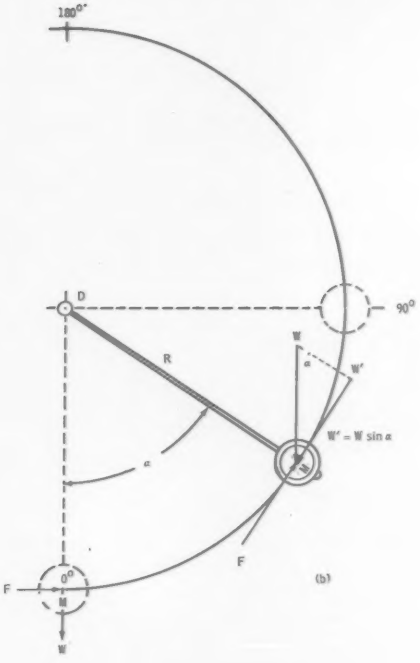
Generating units of utility systems which are equipped with voltage regulators have two regulating devices acting upon them simultaneously. The first of these is the speed governor which controls throttle opening and, therefore, the mechanical torque projected into the generator shaft. It has direct control of the speed of isolated units. However, after the unit is connected to the system, the governor controls the watt power output which is measured by the in-phase current at normal voltage. In this latter case, it becomes an in-phase current regulator.

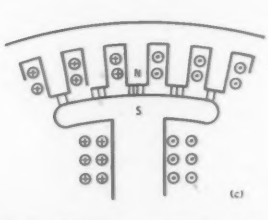
The second regulating device acting on the system is the voltage regulator. Similar to the speed governor, it is not what its name implies since it is not a regulator of voltage directly except prior to the connection of the unit to the system. After connection to the system, the voltage regulator controls system magnetizing current, commonly termed wattless current. This current supplies magnetizing flux for the system apparatus whose magnetizing current is not self-generated or supplied by other means, and lags behind the in-phase power current by 90 electrical degrees.

Displacement angle varies with output

The magnetic field across the air gap, supplied by the rotor current of the generator, interacts with the magnetic field resulting from the stator current to produce a tangential force opposing the mechanical torque of the prime mover and converting it to electrical power. The magnitude of the tangential force between the stator and rotor fields is a function of their angular displacement α as shown in Figure 1a for a cylindrical-rotor machine on an infinite bus with constant excitation corresponding to rated load and power factor. Under normal operation the angular displacement α assumes a value such that the air gap torque equals the prime mover torque. However, if the prime mover torque exceeds the peak of the curve, the rotor is accelerated beyond synchronous speed and synchronism is lost.







DISPLACEMENT ANGLE is governed by the balance between air gap flux strength and the prime mover torque. As the air gap flux is weakened or the prime mover torque is strengthened, the displacment angle increases. **(FIG. 1)**

Because of the nature of the torque angle curve, some operators refer to a generator under load as "leaning against the system."

A mathematical expression for the amount of mechanical power that can be absorbed by the generator and converted to electrical power for a given displacement angle is:

$$P = 3\frac{E_d E}{X_d}\sin\alpha + 3E^2\frac{X_d - X_q}{2X_d X_q}\sin 2\alpha$$

where P is power in watts

E_d is internal machine voltage, line to neutral, in volts

E is terminal machine voltage, line to neutral, in volts

X_d is direct axis synchronous reactance of the machine, in ohms per phase

α is the angle between E_d and E ("displacement angle") in electrical degrees, and

X_q is quadrature axis synchronous reactance of the machine, in ohms per phase

For a cylindrical-rotor machine, X_d and X_q are equal, and the second term of the expression becomes zero. The curve of Figure 1a is a plot of the first term of the expression. Change in excitation results in change in E_d and a new curve with a different peak value.

Perhaps the foregoing can be clarified by an elementary representation of the relation of these two forces, as shown in Figure 1b. Here the generator rotor is represented by a pendulum with mass concentrated at M on a rigid radius arm free to rotate around D. The torque of the prime mover is indicated by the tangential force vector F directed against mass M tending to displace M counterclockwise. The tangential component of the weight of the pendulum is the opposing air gap magnetic force.

Synchronism depends on balanced forces

Since the radius arm totally supports the weight of mass M, with the pendulum in the vertical position shown, there is no opposition between vector W and vector F, and the mass M will move in angular position. This vertical position of the pendulum corresponds to the rotor poles being in radial alignment with the stator poles, as is the case at no load (neglecting losses). This condition is illustrated in Figure 1c, where there is attraction between rotor and stator radially but not tangentially. The rotor must be displaced from this vertical position to build up tangential or circumferential force. It is understood, of course, that the pendulum and vector system would actually be rotating at synchronous speed, but are considered static for the purpose of the analogy.

As mass M moves counterclockwise in response to force F, the vertical force due to its weight builds up in opposition to prime mover force F, due to the increase in the angle at which it acts. Obviously, it becomes maximum when α is 90 degrees and the radius arm is horizontal. Its value at any position is W sin α. At values greater than 90 degrees, this value decreases. This decrease is due to the geometry of the rotor poles and the related magnetic field.

On the other hand, the mechanical torque of the prime mover has a uniform value at all radial positions. For example, in a turbine the fluid carrying the energy acts on blades all around the periphery simultaneously. Suppose, then, the value of the prime mover force F at full load and that of the magnetic force W sin α are such that as mass M moves counterclockwise under influence of force F they become equal and, therefore, in balance at approximately 45 degrees, as shown in Figure 1b.

If a unit were operated under this condition, a considerable increase in prime mover torque F or decrease in magnetic torque W sin α would allow the pendulum to reach 90 degrees or horizontal position which is the "pull-out" point. However, the torque F remains constant for any given setting of the governor. Actually, since sin 45 degrees is 0.707, the margin of decrease of magnetic torque would be nearly 30 percent of full load. This margin will be referred to as the margin of steady state or static stability.

Margin influenced by economy

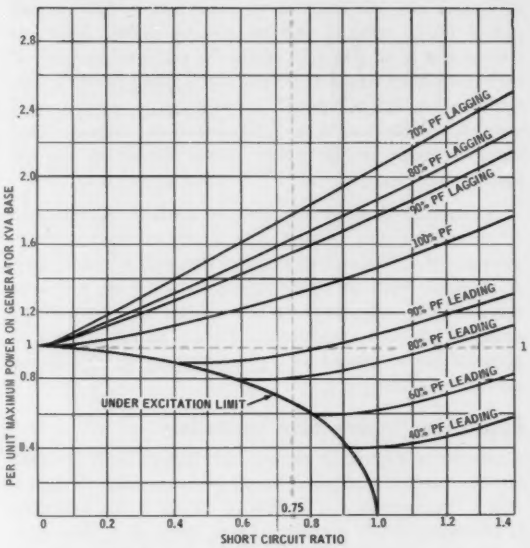
With a 30-percent stability* margin, safe system continuous operation would be assured under practically all conditions. However, this margin cannot always be maintained in practice, particularly at leading power factor operation when the field current necessary for this margin would produce excessive system voltage. To provide a 30-percent margin over the entire operating range would not be economical, as the physical size of the generator would have to be greatly increased. The margin is critical with cylindrical rotors, which are built to withstand the high speeds dictated by prime movers.

Theoretically the smallest generator for a given rating is one that operates at full load with sin α equal to unity. Here there is no margin at all since the unit is operating at the pull-out point. Any overexcitation for margin which results in a lagging power factor also supplies a proportionate magnetizing or wattless current into the transmission system. If the load power factor demands magnetizing current, stability is obtained naturally.

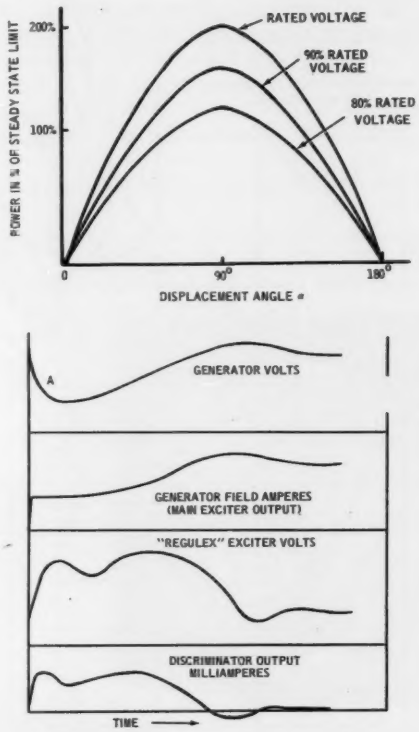
The relation of stability to short-circuit ratio at various power factors is indicated in Figure 2. In this figure no line or transformer reactance is considered. Short-circuit ratio which is indicative of physical machine size for a given rating is plotted as abscissa, and the ratio of maximum steady state power to rated power is given as ordinate. The values in this figure are for fixed excitation, without a voltage regulator and with the generator feeding into an infinite bus, i.e., a system so large that a change in kva or voltage output of this unit will have negligible effect on the system bus voltage.

The prime mover force and the magnetic force at rated load are balanced on horizontal line 1-1. If the generator has a short-circuit ratio of 0.75 and is operating at 100 percent power factor, the stability margin is 30 percent. For this short-circuit ratio the limit of under-excited operation is reached at 66 percent power factor leading

* This stability, which refers to the maximum short-time torque that can be transmitted through a generator and converted to electrical energy, is not to be confused with stability as given in the first article, which refers to "hunting" or oscillating of the regulator system.



POWER FACTOR is indicative of field strength since it is governed by the excitation. A strong field produces a lagging power factor and increases the margin. **(FIGURE 2)**



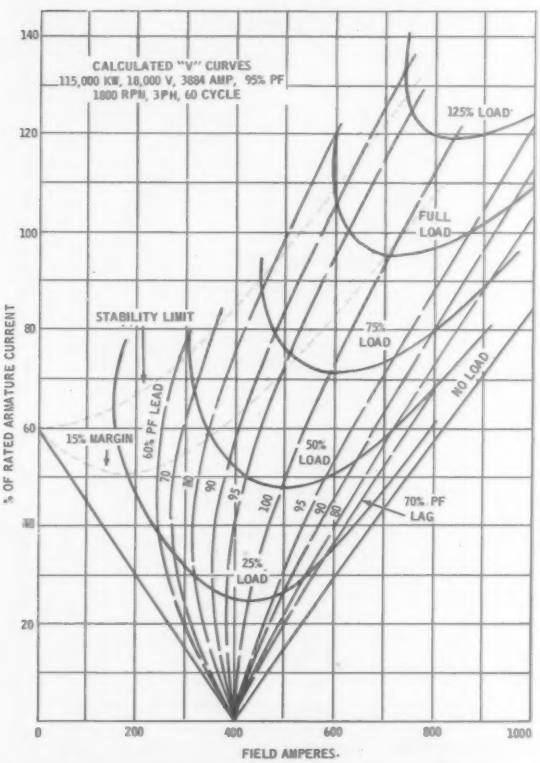
VOLTAGE DIPS which always occur with suddenly applied load tend to reduce pull-out margin. Present-day regulators reverse this tendency. **(FIGURES 3a and 3b)**

and rated kva. An increase in excitation to 100 percent power factor reduces wattless current drawn from the system and in so doing increases the stability margin. If excitation is increased to 90 percent lagging power factor, the stability margin would increase to 56 percent, and wattless current would be delivered to the system. This, however, must satisfy system power factor on wattless current requirements.

A machine with an 0.8 short-circuit ratio operating at 80 percent lagging power factor (over-excited) requires a torque of 1.68 times its rated kva to pull it out of step. A machine with an 0.6 short-circuit ratio, at the same power factor, requires 1.49 times rated kva, both being under steady-state conditions. Hence, as the generator's physical size is reduced for a given kva rating, the pull-out torque becomes less.

Regulators assure safe operation

As shown in Figure 3a, the stability power limit or "pull-out" is materially affected by the percent rated voltage at which the generator is operating. Thus if the generator is operating at 80 percent voltage, there is a 35-percent reduction in the stability power limit. It varies approximately as the square of the voltage. This factor must be considered since system faults caused by lightning or switching cause heavy currents to occur which lag the voltage by 90 degrees and, therefore, tend to demagnetize the generator, that is, act in opposition to the normal excitation in the magnetic circuit. Simultaneously, there is an immediate reduction in terminal voltage on occurrence of the fault. The amount of reduction is determined by the sub-transient reactance. This is illustrated in curve A, Figure 3b. However, if the dynamic stability is considered during the fault condition, it may be found that the effective short-circuit ratio of the generator, under voltage regulator control, is increased two or three times above its normal steady-state value. On fault conditions, the generator stator or armature winding acts as the primary of a transformer and the field as the secondary in which a current, proportional to the rate of change of the short-circuit current, is induced in the direction to sustain flux in the generator. The action of the regulator increases the excitation during the fault thus further increasing the machine flux and, therefore, the stability of the generator. Without the regulator the flux will decrease at a rate determined by the transient reactance, further reducing the terminal voltage and reducing generator stability.



MINIMUM EXCITATION control need is best shown by the generator "V" curves. The effect of load and power factor changes on generator stability can be readily controlled. **(FIG. 4)**

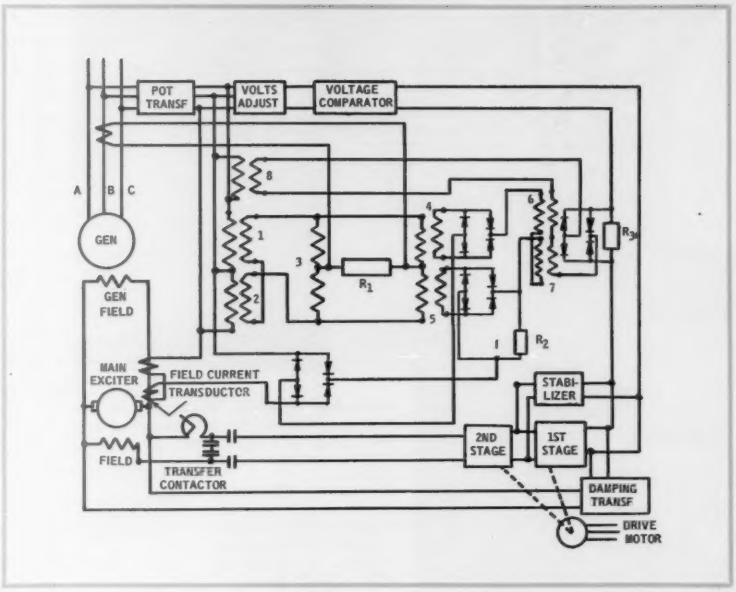
The increased use of high voltage cable in metropolitan areas and the addition of static capacitors to distribution systems has increased system pf. Due to the high pf at load centers, there is no place for extra magnetizing or wattless kva to go except to raise system voltage until it is dispersed needlessly. Thus with general increase in system pf, as shown in Figure 2, higher short-circuit ratio machines are demanded unless reliable regulators are supplied to give safe system operation at low stability margins.

With the manual generator control, it is necessary to readjust excitation, during daily load changes, and to carefully keep a ratio between load current and excitation. This method of control leaves only a small margin for "riding through" a system fault.

One generating unit with a short-circuit ratio of 0.66 was purchased a number of years ago and was operated many years with manual excitation control. The "V" curves for this unit are shown in Figure 4. The steady growth in static capacitors on the system reduced excitation requirements until the unit fell out of step a few times during disturbances in the summer months. By adding minimum excitation control, a sufficient margin in stability was secured for all conditions without manual supervision.

Regulator prevents underexcitation

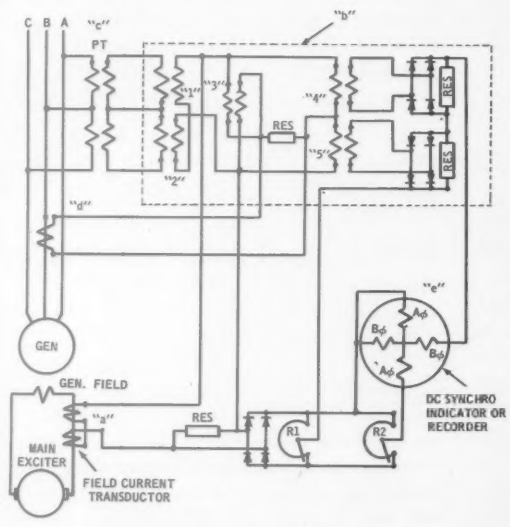
The automatic minimum excitation control circuits in Figure 5 are shown in schematic form whereas the remaining equipment which has been discussed in previous articles is shown in block form. The device consists of several isolating and phase-shifting transformers 1, 2, 3, 4, 5, 6, 7, and 8 which receive excitation from potential transformers and one current transformer. The current transformer supplies a voltage signal across resistor R_1 which is proportional to the synchronous machine current and vectorially coincident. This current signal is injected at the mid-point of an autotransformer "3" so that it vectorially adds to one half and subtracts from the other half of the autotransformer voltage. The resultant ac signals are respectively

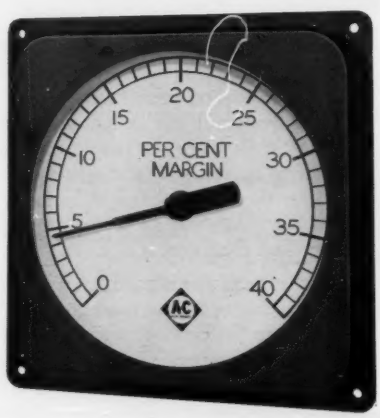


FIELD CURRENT measure taken from a transductor is used as a control signal which is fed into a combination of static components that automatically calculate and control minimum excitation. **(FIG. 5)**

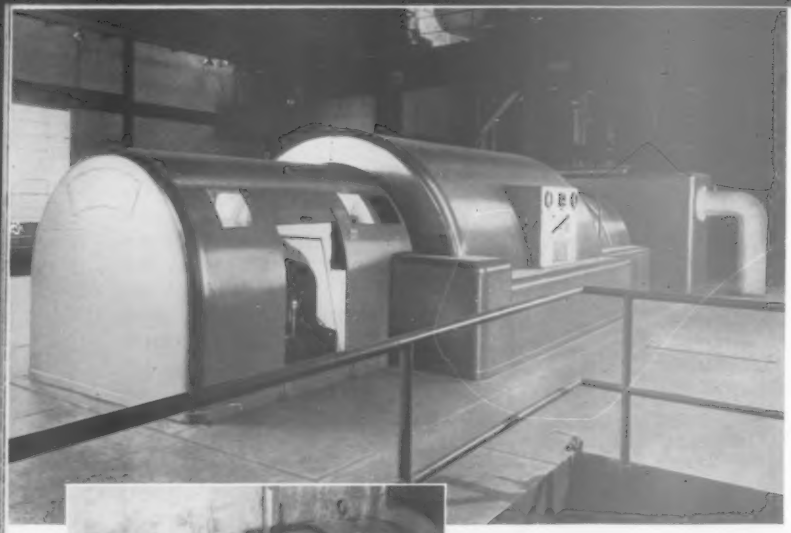
fed to isolating transformers "4" and "5." If the machine current is purely reactive, the resultant signals at "4" and "5" increase equally. If the machine current is at unity power factor, the voltage at "4" increases, but decreases at "5." Rectifiers in the secondary circuits of "4" and "5" are connected in opposition so that only the arithmetic differential voltage signal appears. This dc signal voltage is directly proportional to the in-phase component of current, regardless of variations in machine power factor.

The dc side of the rectifiers across "4" and "5" are connected in opposition to the signal from the field current transductor. If the field current signal is greater than the in-phase signal, no current can flow through the magnetic amplifier "6" and "7" because of the unidirectional characteristic of the rectifier. If the field current signal drops below the in-phase signal, the differential signal causes a current through the magnetic amplifiers "6" and "7." This signal is amplified by the magnetic amplifier and is recti-

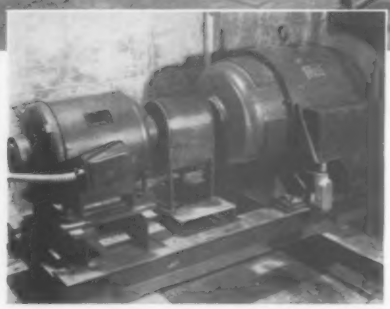




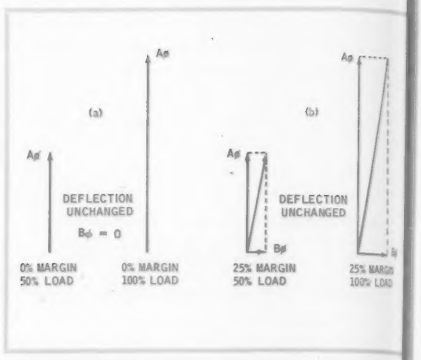
STABILITY MARGIN indication enables the operator to anticipate the pull-out risk under all operating conditions. With this knowledge, excitation can be safely held at a minimum for the most economical operation of the generator. **(FIG. 6)**



MODERN 15,000-kw, 80-percent, 12,500-volt generator is the most important unit on a small midwestern power system.



GENERATOR voltage regulator with its rotary amplifier is usually in some remote location.



STABILITY INDICATOR operation is consistent regardless of load conditions because receiver phases remain in the same balance. **(FIGURE 7)**

fied and fed to the *Regulex* exciter control field with the polarity for boosting excitation. The excitation increases until the minimum preset ratio of excitation to "in-phase" current is again established.

This control device automatically maintains the preset ratio with varying power load conditions with one adjustment. The actual presetting is made for the desired percent stability reserve which depends on the machine constants such as short circuit ratio and synchronous impedance.

Stability reserve is indicated

If the excitation system is controlled by a voltage regulator, the capacity of the machine to pick up sudden load increments is greatly increased. However, if an automatic minimum excitation control is not installed, the responsibility for presetting the excitation for steady-state stability is in the hands of the station operator. To allow the operator to conveniently and quickly meet this responsibility, the use of a stability indicator will tell him at a glance how much margin he has on a given machine for a given load condition.

Knowledge of the allowable load pick-up at any time and under any operating condition enables the operators to intelligently distribute reactive power between generators or stations, and a system disturbance will not find some one machine unable to assume its anticipated share of additional load.

The operation of the stability indicator is almost the same as that of the automatic minimum excitation device. Instead of controlling a *Regulex* exciter field, the stability signal is fed to a dc synchro receiver indicator as shown in Figure 6. The field current transductor "a" provides an output current signal proportional to the field current but electrically isolated, and independent of generator temperature variations.

The second unit "b" is energized by potential and current transformers "c" and "d" which produce a dc signal that is directly proportional to the power component of the generator line current.

The two signals from "a" and "b" are directed to the dc synchro indicator "e," which assumes a definite position for any one ratio of the two dc signals. This device, which has a two-phase stator and a permanent magnet rotor, functions without slip rings or torsion springs and has but one moving part.

Figure 7 shows how the deflection of the indicator varies as the percent reserve margin is changed. Figure 7a shows no change in the indicator position as the load is increased from 50 percent load to 100 percent load with 0 percent margin. Figure 7a also shows that no change in deflection will occur if a 25-percent margin is maintained as the load is increased from 50 to 100 percent load.

If a 25-percent reserve were indicated, the operator would know that without a change of excitation the generator could pick up a load increase up to 25 percent of the existing load.

Condensers need excitation limit control

The equipment developed for minimum excitation control for generators conveniently fills other needs. Most synchronous condensers can supply full rated lagging current at little or no excitation. Momentary reversals might occur with a high amplification type automatic voltage regulator. This reversal would cause the synchronous condenser to slip a pole. The use of the minimum excitation control as a zero excitation limiter allows full-rated machine capacity with pull-out protection and yet allows full positive to negative field forcing from the *Regulex* exciter for fast response.

The device is schematically shown in Figure 8. It is energized by a single-phase voltage from potential transformer "a" and by the exciter armature voltage. If the exciter voltage is the polarity shown, no current can flow through the magnetic amplifier input because of the unidirectional current characteristic of the rectifier. If the exciter voltage reverses slightly, the blocking rectifier conducts a small current which is amplified by the magnetic amplifier, rectified, and fed to the *Regulex* exciter control field with the polarity which boosts excitation. The excitation increase continues until the exciter voltage approaches a zero minimum.

Another device used in controlling some synchronous condensers is a preset minimum excitation limiter. This device allows the manual setting of the lower operating band of excitation.

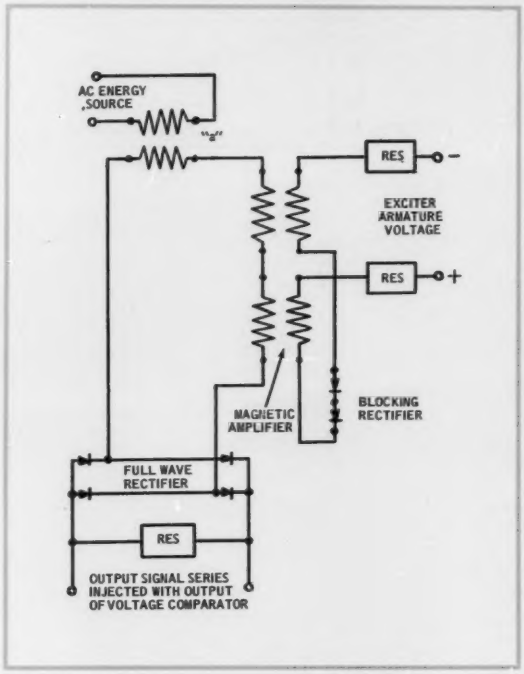
Functionally, this device limits the under-excited reactive power at the machine terminals, not only for abnormally high line voltage conditions but also if the regulator voltage adjusting control is set so low by the operator as to exceed machine current capacity.

Figure 9 shows the device as being energized by a single-phase voltage and by the exciter armature voltage. The single-phase voltage is fed through a constant current network consisting of capacitor C_1, resistor R_1 saturating reactor "5" and rheostat RH_1. This network provides a constant current through the rheostat substantially independent of variations of the ac energy source. An adjustable portion of the voltage is compared. The rectifier is connected in series and in opposition to the armature voltage. If the exciter armature voltage is greater than the adjusted reference, no current can flow through the magnetic amplifier "3" and "4" input because of the unidirectional current characteristic of the rectifier. If the exciter voltage drops below the adjusted reference, the differential voltage causes a small current to flow through the magnetic amplifier input. This current is amplified and fed to the *Regulex* exciter control field with the polarity which boosts excitation. The excitation increase continues until the exciter voltage again approaches the adjusted reference.

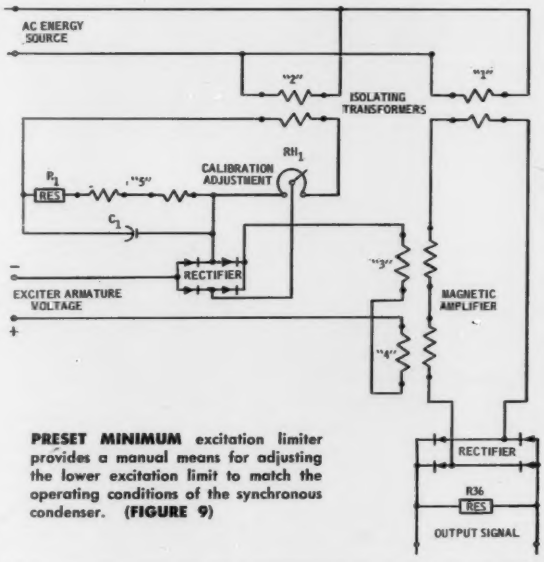
Consider economy

With oversize generators and over-excitation, the pull-out risk can be greatly minimized. However, this practice is no longer considered economical and does not provide ample protection without regulators. Modern rotary type voltage regulators with static control components can prevent pull-out even with low short circuit ratio generators operated with a small stability reserve. Thus the cost of the generator is lower since it can be built smaller for the same rating. The reduction of margin also limits the generation of wasteful reactive power into the system.

Where modern regulators with minimum excitation control are not used, the operator can approach this economy by referring to a stability reserve indicator and adjusting the machine's excitation to a safe minimum.



FULL USE of high amplification rotary type regulators can only be made if a zero excitation limiter is used to prevent momentary reversal of the synchronous condenser field excitation. **(FIGURE 8)**



PRESET MINIMUM excitation limiter provides a manual means for adjusting the lower excitation limit to match the operating conditions of the synchronous condenser. **(FIGURE 9)**

THIS 21-PANEL *DUPLEX* switchboard controls four 50,000-kva synchronous condensers, five 50,000-kva transformers and four 161-kv transmission lines with carrier current protective relays. All indicating instruments are mounted on front panels, while protective relays are placed on rear panels, not shown. Switchboard can be entered from either end.

A-C Staff Photo

PT'S Are Getting Smaller

by D. R. LAIB
Instrument Transformer Section
Allis-Chalmers Mfg. Co.
Pittsburgh, Penna.

Potential transformer weights and sizes are now greatly reduced through the use of new coordinated insulation principles that result in the elimination of corona.

RADICAL CHANGES in transformer construction are best reflected in today's potential and current transformers where the weights and dimensions are being reduced to a size commensurate with the energy output. As a result of recent research and development work on the behavior of insulating materials under varying electrical stresses, the new transformers are smaller, more efficient and suitable for long service with a minimum of care and attention.

New studies of dielectric losses, temperature rises, heat dissipation, drying techniques, and insulation power factors were the first steps in new lines of instrument transformers. This discussion of the designing, testing and placing in production of an entirely new line of high voltage potential transformers is an interesting example of how recent advances in materials and techniques can benefit users of electrical equipment. Figure 1 shows the four different voltage rating transformers 24, 34.5, 46 and 69 kv, all similar in mechanical construction.

Potential transformers are required to produce only small power output and, for the sake of economy in design, the coils must be composed of a large number of turns of small gauge conductors, i.e. the transformer will operate at low volts per turn. The high reactance of a coil of this construction presents an infinite impedance to a high frequency surge and, hence, the energy of a surge impact is dissipated through the capacitance circuits of the assembly. This necessitates careful selection of the kind of insulation in the coil and the coordination of insulation strength throughout the primary coil assembly at all points of electrical stress.

Calculation determined that a four coil primary winding, assembled over a single layer secondary winding as shown in Figure 2 would give desirable voltage distribution throughout the primary coil stack without a concentration of excess voltage at the line ends. In governing this voltage distribution, it was necessary to choose a factor derived as the square root of the quotient of the winding to ground capacitance and the total series coil capacitance. This factor must not result in charging current and low frequency reactance that would act adversely to the ratio and phase angle characteristics of a metering transformer.

High stress points are protected

To relieve voltage stresses on the line end coils a static shield like that shown in Figure 3 is assembled at each end of the coil stack. The shield consists of a copper ring with an inside and outside diameter approximately equal to the inside and outside diameters of the primary coils. A small radial section of the shield is removed so that it does not constitute a shorted turn. The shield is placed adjacent to and insulated from the outside surface of the end primary coils.

A heavy lead from the static shield is electrically connected to the line lead of the primary coil, forming a

REDESIGN FOR SIZE REDUCTION provided an opportunity to incorporate other features such as a hermetically sealed case and an oil level indicator in one primary bushing. **(FIGURE 1)**

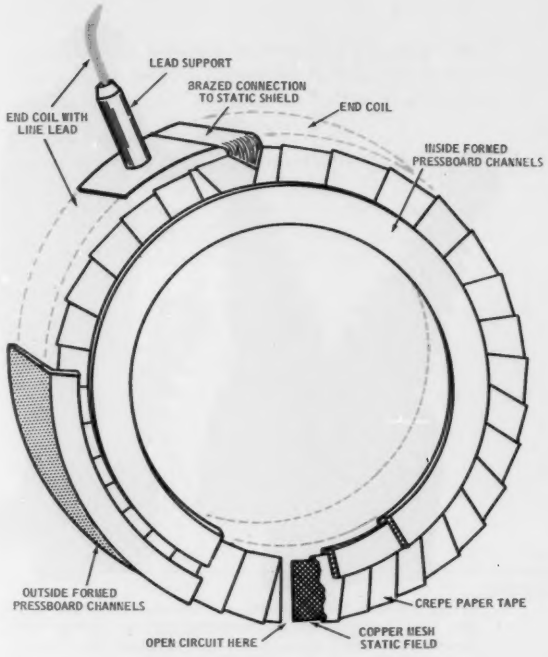
strong mechanical support.* The shield acts to remove the electrical stress to ground from the end coils of the primary winding and distributes it over a plane surface. Double channels provide protection at the inside radii of the shields where the greatest electrical stresses occur both in steady state and impulse disturbance conditions.

All coil edges and corners are protected by means of formed insulating channels and angles which fit closely to the coil surfaces, effectively prohibiting the formation of corona and the development of leakage paths. This combination results in a design which stands long continued voltage stress and short time surge conditions.

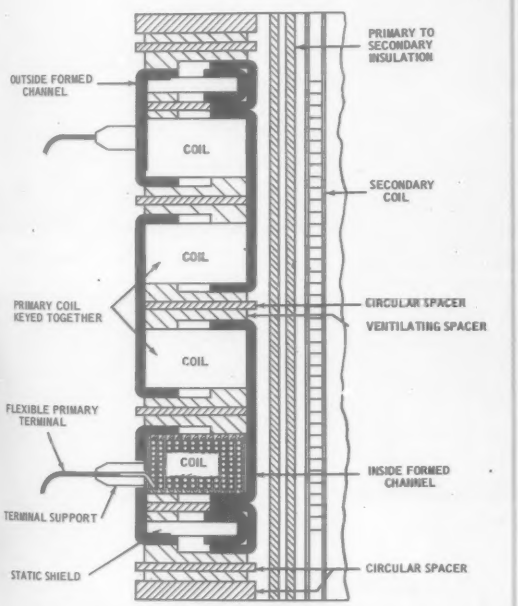
Figure 4 is a section of the assembled transformer showing the primary lead construction. A steel tube forms the supporting member for the lead which is centrally located by means of concentric insulating tubes. Here again the points of greatest stress at the ends of the steel supports require additional insulation which was provided by the insulating channels shown.

Reducing the physical size of the potential transformers normally would cause restriction of oil flow and thus produce hot spots. Hot spots are eliminated since the insulating oil also serves to dissipate heat generated by dielectric losses. The coil and insulation of a two-bushing, 69,000-volt transformer is constructed with the primary

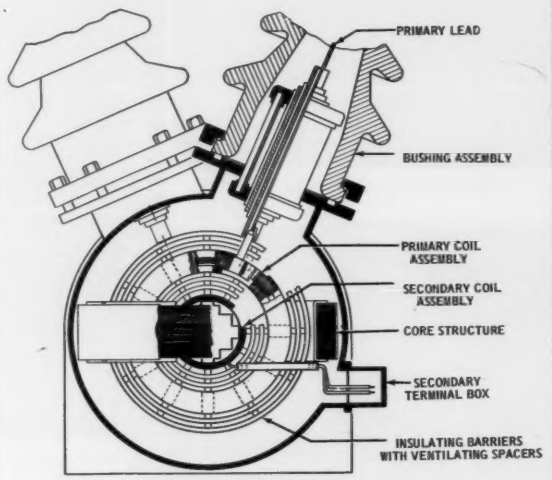
* *"Coordinated" Insulation — New Transformer Milestone* — Foster, S. L., Allis-Chalmers *Electrical Review* — First Quarter 1949.



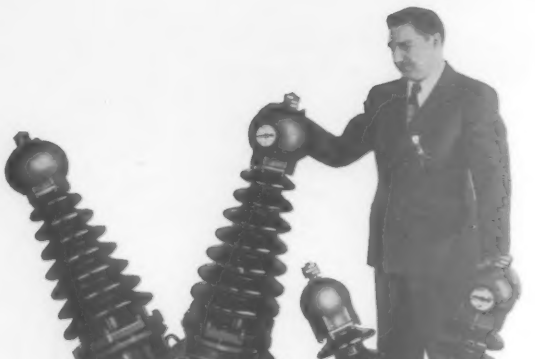
STATIC SHIELD is used to protect the insulation of the end coils. The shield which is a ring of copper mesh cut so that it does not form a shorted turn is carefully insulated from ground. **(FIGURE 3)**



FORMED CHANNEL insulation is used on the primary coils of this 69-kv potential transformer to eliminate corona which gradually deteriorates insulation, forming leakage paths. **(FIGURE 2)**



STRESS POINTS in primary bushing insulation require the same care as those in primary coil insulation. Channel insulated steel tubes serve as primary lead supports. **(FIGURE 4)**



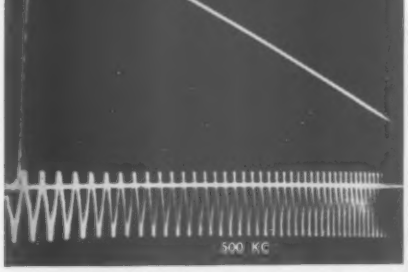
CLOSE FITTING INSULATION and reduction of internal losses plus free circulation of the insulating oil for cooling makes possible these small size transformers. **(FIGURE 5)**

to secondary insulation formed of concentric insulating tubes, evenly spaced to allow for unrestricted oil circulation.

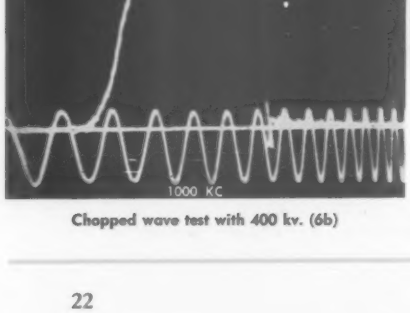
To provide the safety factor required by standard 60-cycle induced tests, the individual primary coils are layer-wound with untreated paper insulation between layers. Coils are held in separation by circular spacers, to which radial ventilating spacers are secured, so that edges of all coils are in direct contact with freely circulating, cooling and insulating oil. Coils 1 and 2 which are connected in series electrically at the inside layers are keyed together mechanically by inside formed circular insulating channels. Coils 3 and 4 are secured in the same manner. Coils 2 and 3 are electrically connected at the outside layers and are held in position by outside formed circular, insulating channels.

Care required in manufacture

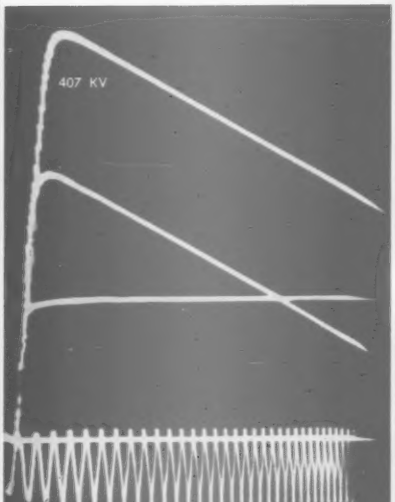
Reducing the physical size of transformers also places greater importance on care and precision needed in manufacture. In maintaining the best possible insulation power factor, every precaution must be taken to keep the insulation clean, dry and free of any mechanical defects. Before the final addition of the lead assembly and porcelain, the



Full wave impulse test at 350kv. (6a)

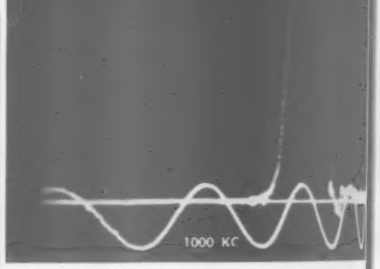


Chopped wave test with 400 kv. (6b)

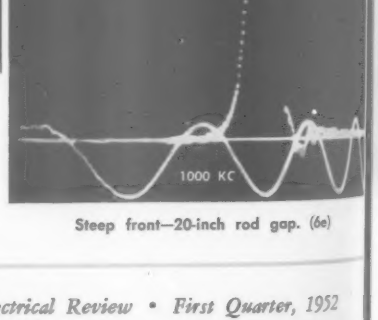


Full wave test with ½-40 wave. (6c)

IMPULSE TESTS prove that these 69-kv potential transformers will withstand the most severe operation conditions. **(FIG. 6)**



Steep front—14½-inch rod gap. (6d)



Steep front—20-inch rod gap. (6e)

transformer is subjected to a vacuum drying process, which is continued until the insulation power factor reading is under one percent. With everything in readiness the final lead assembly is added before the coils can cool sufficiently to absorb any moisture. Oil-tight construction is obtained by clamping synthetic gaskets between the machined steel flanges and the ground porcelain surfaces.

Oil is admitted to the transformer case, under vacuum, to the proper oil level after which the vacuum is released and the assembly hermetically sealed. An oil gauge is provided on one primary terminal as shown in Figure 1. Sufficient air space is provided above the normal oil level to allow for temperature changes without an excessive build up of internal pressure.

Figure 5 shows a 25-kv and a 69-kv in comparison and gives an idea of the relative physical dimensions. With these small dimensions and reduced amount of active material, there is a decrease in internal losses which makes improved performance possible, both in ratio and phase angle characteristics. The fact that the steel core and the copper in the windings are in intimate contact with the cooling oil makes possible high kva output of the designs without exceeding the standard 55-degree C rise. The 69-kv transformer has a thermal rating of 6.5 kva. The 46-kv, 34.5-kv, and 25-kv transformers have thermal ratings of 4.5, 4.5, and 4 kva respectively.

Results are checked by tests

A series of tests were made on several transformers of each insulation class to prove the strength of the barrier, coil and layer as well as the turn-to-turn insulation.

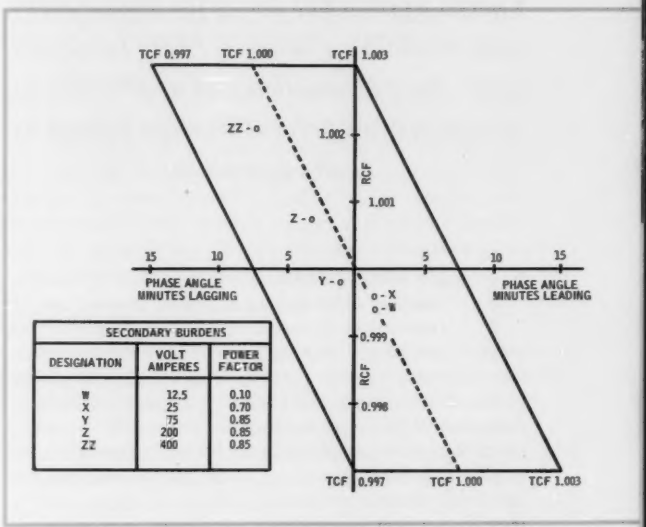
Figure 6 shows typical oscillograms of impulse tests made on a two-bushing, 69-kv transformer. The last three films represent only a few of the many shots that were given, above standard requirements, to prove that weakening of insulation would not occur under severe service conditions. One transformer was excited at 90 kv, with one terminal grounded, for one month. Upon disassembly, a careful check showed no deterioration of insulation or signs of excess heating.

Typical performance of the 69-kv transformer, plotted on a parallelogram for 0.3 accuracy, is shown in Figure 7. The points for standard metering burdens W, X, Y, Z, and ZZ are all well within the specified area for what is defined as the 0.3 accuracy performance class.

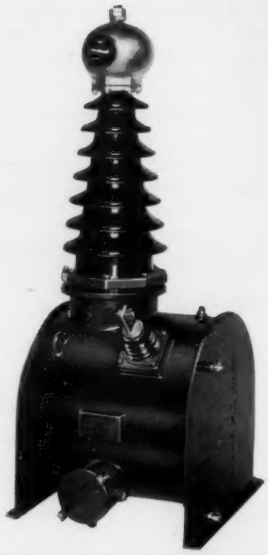
Since high voltage potential transformers were designed with coordinated insulation in primary leads, primary coils, and insulation-to-grounded parts, test results bore out the value of this type of design and showed that the transformers will withstand surge conditions in excess of standard full wave and steep front impulse tests. The insulation and ventilation was designed to continue indefinitely to withstand 60-cycle voltages 30 percent above their individual transformer ratings. The construction makes possible a thermal rating greater than was formerly possible in these physical sizes of potential transformers. This lightweight assembly, occupying small space, develops operating characteristics equaling the best metering accuracy specified by present standards.

Single-bushing potential transformers like that shown in Figure 8 are used for connection between the line and neutral on three-phase wye systems. Two separate secondaries provide the required ratios.

With care in the selection of insulating materials, a good factor of safety is built into present day transformer assemblies. More compact units with properly fitted housings are resulting in substantial savings of critical materials, and in volume and weight of insulating oil.



TYPICAL ACCURACY of these potential transformers is shown by results of tests with various secondary burdens. The parallelogram represents the limits of accuracy. **(FIGURE 7)**



SINGLE BUSHING potential transformer rated 40,250 to 67,08/115 volts and insulated for 69 kv is used in three-phase four-wire systems to measure line-to-neutral voltage. **(FIGURE 8)**

Safeguarding LARGE AC MOTORS

There's a protective device for almost every fault condition a motor is likely to experience. Proper selection and application of safeguards can prevent damage caused by faulty operation.

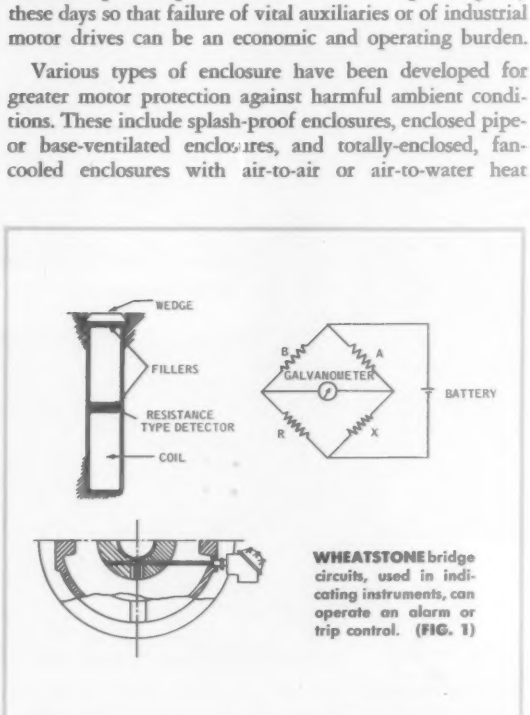
by F. C. OSTERLAND and E. N. GIGOT
Motor-Generator Section
Allis-Chalmers Mfg. Co.

THE PERFORMANCE and reliability of essential auxiliary drive motors in central stations, and of large motor drives in industrial applications, has become increasingly important. In central station design, the unit principle places a greater premium on performance of essential auxiliaries. Duplication of equipment as operating reserve for major auxiliaries is either held to a minimum or avoided completely, thus further accentuating the need for greater reliability. Both central stations and industrial plants operate with little or no spare capacity these days so that failure of vital auxiliaries or of industrial motor drives can be an economic and operating burden.

Various types of enclosure have been developed for greater motor protection against harmful ambient conditions. These include splash-proof enclosures, enclosed pipe- or base-ventilated enclosures, and totally-enclosed, fan-cooled enclosures with air-to-air or air-to-water heat exchangers. In addition, standard relays furnished on motor controls normally give protection against:

1. Sustained short circuits (overcurrent relay)
2. Excessive overloads (thermal overload relays)
3. Prolonged operation at harmful low voltage (time-delay undervoltage relay)
4. Prolonged operation out of synchronism on synchronous motors (incomplete sequence and temperature squirrel-cage protective relay, and pull-out feature on field application relay)

However, it is often advisable to provide additional protection at the motor against extended damage due to internal faults and excessive temperatures.



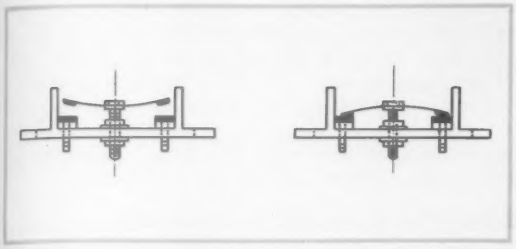
WHEATSTONE bridge circuits, used in indicating instruments, can operate an alarm or trip control. (FIG. 1)

Protection has many forms

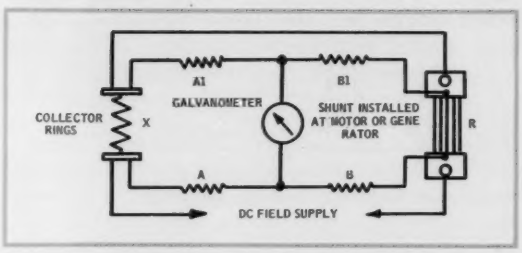
Protective devices can be arranged to perform various functions when protecting motors. In unattended applications, or applications where stopping of the motor will not seriously affect production, the device can stop the motor automatically when a dangerous condition exists. In other applications, where a loss of production or other hazards occur when a motor ceases to operate, the device can cause a bell to ring, horn to blow, or lamp to light, to give advance warning of an approaching dangerous condition.

A common protective precaution is the detection of excessive temperatures in the stator coil and core structure, which might cause the insulation to deteriorate, and in time lose its mechanical strength and insulating qualities. Overheating can result from such causes as too frequent starting, excessive overloads, high ambient temperatures, abnormal voltages, ventilation failures, failure to start, stalled condition, or phase failure. Excessive stator temperatures can be detected by a simple, bimetallic disc type thermostat, or by imbedded temperature detectors.

Temperature detecting devices are of value, too, as accurate and reliable guides for maximum safe loading.



DANGEROUS TEMPERATURE causes the normally open bimetallic disc to snap down, closing alarm circuit. Circuit will open as disc snaps upward when normal safe temperature is reached. **(FIGURE 2)**



SIMPLIFIED KELVIN BRIDGE circuit is used to determine synchronous machine field temperatures where field resistance is too low for application of the Wheatstone bridge principle. **(FIGURE 3)**

If a unit is loaded according to ammeter and wattmeter indications, a safety factor must be allowed, with avoidable loss of capacity. By using temperature as a guide, however, the equipment can be loaded right up to the safe limit.

Embedded detectors

For motors 1000 hp and larger, where the stator slot size permits use of the embedded detector, this method of temperature indication is desirable. Usually, the detectors are copper resistance units, with a resistance of 10 ohms at 25C, and are located in the coil slots, between the top and bottom coil side, and midway between the ends of the core. Normally, six detectors are spaced equidistant around the stator winding of the machine. Leads are brought out from each detector to an enclosed terminal board mounted on the stator yoke. A selector switch is used to connect the leads of any one detector to an indicating instrument on the control panel.

Indicating instruments have proved themselves to be reliable in power plant and industrial service. Measurements reflect only temperature changes in the detectors, other variables being compensated for or eliminated. Detectors can be located at widely varying distances and connected to the same instrument.

Wheatstone bridge

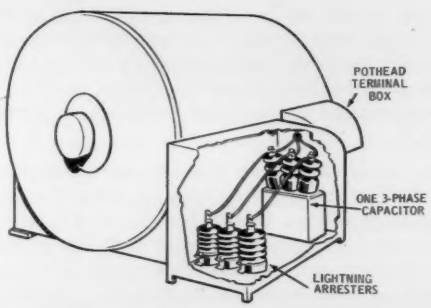
The Wheatstone bridge principle is used in instruments connected to resistance temperature detectors, as shown in Figure 1. Measurement depends on the fact that the resistance of a suitable wire coil changes as temperature changes, and that this resistance at a given temperature is always the same. In the balancing type of instrument, the detector resistance is balanced against an adjustable standard resistance calibrated in degrees, with a galvanometer to indicate the balance point or zero reading in the bridge circuit. In the indicating type, the standard resistance is fixed, and the unbalance indicated by the galvanometer is calibrated in degrees. The detectors can also operate an alarm, or trip the control contactor, if additional relaying is provided. Both the selector switch and indicating instrument are normally specified with the control equipment.

In this method of temperature measurement, the unknown arm X is a resistance type temperature detector embedded in the stator winding or bearing metal. Using three leads from the detector, this principle has one of two equal leads connected in bridge arm R to compensate for resistance of lead remaining in detector X, so that the junction between arms X and R is at the detector. The third lead from the detector goes to the battery. Variable arm R is calibrated in degrees and adjusted so that galvanometer reads zero and resistances balance.

Disc thermostats

For most motors below 1000 hp, the bimetallic disc thermostat, shown in Figure 2, is recommended as a temperature protective device that can be mounted on the stator windings or core. The operating element is a bimetallic disc which snaps open or closed, depending on whether it is normally closed or normally open, when excessive heat endangers the motor. The disc returns to its normal position when the motor cools to a safe temperature. Temperature settings must be predetermined, and the disc designed accordingly.

The normally open type is used to close independent signal circuits. If more than one thermostat is used, they must be wired in parallel to assure that the closing of any one will operate the signal. The alternate, or normally closed type, is used primarily to break the control circuit of the motor starting equipment. If more than one thermostat of this type is used, they must be wired in series. The normally closed type can also be used to operate a signal device in conjunction with a relay.



LOW PROTECTIVE RATIO lightning arresters between machine terminals and ground protect insulation against excessive surge voltages caused by lightning or fast-operating circuit breakers. **(FIGURE 4)**

Kelvin bridge for rotor temperatures

Rotor winding temperatures of induction motors are not readily measured, but the field windings of synchronous and dc machines can be measured by resistance methods. This is done by comparing the hot resistance, using the voltage and current through the winding while in operation, to the cold resistance, measured at normal room temperature after the machine has been idle for some time.

It is not general practice to provide protection against overheating of rotor windings, because most conditions which cause rotor overheating will also cause stator overheating. The necessary protection is ordinarily provided by the stator temperature detectors. Synchronous motor rotor temperatures can be measured and recorded by instruments, although this method is usually employed only on very large generators and motors where the machine is equipped with a pair of insulated brushes on the field collector assembly. This provision, along with a calibrated shunt in series with a field circuit, enables connection to a Kelvin bridge in the measuring instrument so the resistance can be determined accurately. The resistance varies with the temperature. When its value at one temperature is established, the resistance measured at some other temperature is an index of that temperature. The measuring instrument can oe calibrated to indicate temperature directly, and actuate an alarm if excessive temperatures are reached.

Figure 3 shows the connections of the simplified Kelvin bridge circuit. Temperature of field X is read or recorded on a calibrated instrument that varies the ratio of resistance B to A and B1 to A1, with B = B1 and A = A1, until the galvanometer deflection is zero, and electrical balance exists between potential points at rotor field collector rings (insulated brush on each ring) and potential points on known shunt resistance R.

Surge dangers minimized

With the increasing use of large motors at higher voltages, protective equipment against excessive surge voltages due to lightning or fast-operating circuit breakers is sometimes desirable. The insulation stress between the winding and frame of the machine is determined mainly by the magnitude of the surge voltage to ground, while the stress on the turn insulation is more a function of the rate of rise of surge voltage as the surge penetrates the winding. Limiting the surge voltage to ground sufficiently to protect major insulation usually requires a special low protective ratio lightning arrester connected between each machine terminal and the grounded frame, as shown in Figure 4.

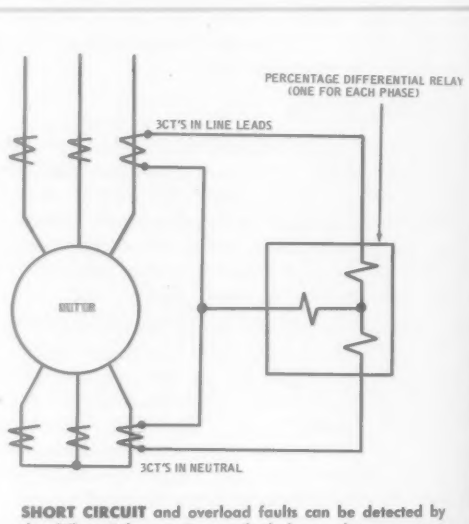
Turn insulation protection is provided by sloping the wave front of the incoming surge to reduce the rate of rise of surge voltage. This is done by using special protective capacitors connected directly from line to ground at the machine terminals. A voltage surge, after passing through a series impedance, charges the capacitor and reduces the rate of surge increase. These lightning arresters and shunt capacitors can be mounted at the motor terminals to provide protection at the motor. This arrangement places the protective equipment back of a breaker, and within the zone of differential protection, and also in close shunt relation to the machine and in the direct path of any incoming surge. Protective capacitors at machine terminals are of further value where unexcited motors or generators have full voltage applied in starting. The resulting switching surge of steep wave front is minimized by the capacitors before it can damage the windings.

Differential protection is dependable

Thermal overload relays with instantaneous overcurrent attachment or overcurrent relays mounted on the motor controls give a certain amount of protection from damage due to normal overloads and short circuits. They will disconnect the motor from the line, but the selectivity requirements may prevent the use of low current or fast time settings, and the necessary lack of sensitivity will reduce the degree of fault protection afforded.

Short circuits in the stator windings of ac machines require the repair and replacement of damaged stator coils. Stator core iron can also be "burned," requiring replacement. In addition, the sustained short circuit can ignite the insulating material, resulting in a fire that will support itself and continue to burn after the electric arc has been extinguished. Repairs involving the replacement of "burned" stator iron are costly, putting the machine out of service for a comparatively long time. The differential protection method of fault detection, shown in Figure 5, helps to avoid such extensive damage, and minimizes the disturbance caused by such faults to the rest of the power system.

NEMA Standards on Switchgear recommend differential protection on motors above 500 hp when rated voltage is above 5000 volts, or above 1500 hp when rated voltage ranges from 2200 to 5000 volts. Each end of each phase winding must be brought out at the motor



SHORT CIRCUIT and overload faults can be detected by the differential protection method shown above, preventing extensive machine and system damage. **(FIGURE 5)**

terminals, since the differential scheme balances secondary currents in current transformers mounted at each end of each motor phase. The differential protection scheme is very sensitive and selective, in that it detects faults within the motor only. Its exceedingly fast operation provides maximum protection against either phase-to-phase or ground faults within the machine.

In rotating machines that are wye connected, three current transformers can be mounted at the machine terminals at the wye. The other three current transformers on the line side can be mounted in the controls. However, for delta-connected machines, all six current transformers must be mounted at the motor terminals to provide the necessary differential protection. In the case of wye-connected machines, the motor manufacturer provides a suitable box and leads for the mounting of current transformers, usually supplied by the control or switchgear manufacturer so that they will match those furnished in the controls. It is important that all six current transformers have identical characteristics.

Devices eliminate moisture, water problems

Excessive moisture may cause a failure in insulation which is otherwise in good condition. A rather common motor accessory, offering protection against moisture during shutdown periods, is the space heater shown in Figure 6. This electrical heater has a capacity of approximately .10 to .50 percent of the machine rating, operated from a 110, 220, or 440-volt ac source. Space heaters maintain the temperature of the machine well above the dew point to prevent condensation of moisture and consequent damage to winding insulation. Heaters are mounted inside the motor enclosure, and leads are brought out to a small conduit fitting near the main terminal leads. They can be furnished for both open and enclosed motors.

Totally-enclosed motors with air-to-water heat exchangers raise special problems relating to the cooling medium. A resistance type temperature detector, similar in principle to those used in the stator winding, or a bulb type thermometer with alarm contacts can be used to measure motor air inlet temperature, which will rise above the normal 40C maximum temperature if the cooling water supply is restricted unduly, or if cooler operation is deficient for any other reason. A water-flow indicating instrument can be used to assure operators of continuous flow of cooling water through the cooler. This instrument not only shows the amount of water flowing, but in the event of complete water failure it activates alarm contacts to close an alarm circuit. With suitable relays, these protective devices can be arranged to open the main motor circuit.

To prevent damage to motor windings from leakage in the water chambers, double-tube heat exchangers are sometimes used. Cooling water normally circulates through the inner tube. The outer tube prevents water from escaping into the motor in the event of failure of the inner tube. The presence of liquid inside the motor enclosure can be detected by use of a liquid level indicator, mounted in the motor base. This, too, can be arranged to activate an alarm circuit or to open motor contactors.

SPACE HEATERS provide protection against moisture damage to insulation and other machine parts. Top illustration shows heater arrangement for a 1250-hp totally-enclosed squirrel-cage induction motor. Bottom photo shows heater set in lower bearing housing of a 450-hp vertical induction motor. **(FIGURE 6)**

Instruments protect bearings

Accessories for protection of large motors against bearing failure are often used but are limited to oil lubricated bearings. Normally, anti-friction bearings are grease-lubricated, and the mounting of a temperature indicating device is not practical. Also, there is no stationary metal part in which to place the temperature indicator. However, with periodic inspection and the proper amount of lubrication, anti-friction bearings are satisfactory on motor ratings below approximately 1000 hp within the speed range where this type of bearing can be used.

Sleeve bearings may be provided with thermostatic relays adjusted to actuate an alarm or trip circuit if the bearing temperature exceeds safe operating limits. The relay is adjusted to reset when the bearing cools to a predetermined safe temperature. Expansion of vapor in a tube located in the bearing metal acts on a sylphon bellows set in the lower part of the operating element. A mercury switch opens and closes the alarm or trip circuit. The relay can be mounted on the bearing itself, or, by means of a tube extension, remote from bearing.

For motor installations that are more or less under continual observation, the bearing temperature relay is sometimes replaced by an indicating thermometer. This dial instrument, mounted on the motor, is tube-connected to a vapor pressure bulb inserted in the bearing metal. The tube extension is of small diameter but is quite durable. Sometimes, however, an armored cable is used for additional protection. This thermometer can be equipped with

alarm contacts to energize an alarm circuit when the maximum allowable bearing temperature is reached.

Centralized temperature readings

For some installations, a system of bearing temperature indication similar to the stator winding resistance detector is preferred. Large electric power stations, in particular, may prefer this method so that temperatures of a number of bearings can be read or recorded at a control center. Oil-lubricated motor bearings can be equipped with the resistance detector embedded in the bearing metal with the three leads of each brought out to a conduit fitting. In this case, the instrument furnished with the control must be an indicating or recording Wheatstone bridge with an alarm device. This type of detector has also been used on large vertical motors and generators where a number of detectors can be inserted in the shoes of the vertical thrust bearing.

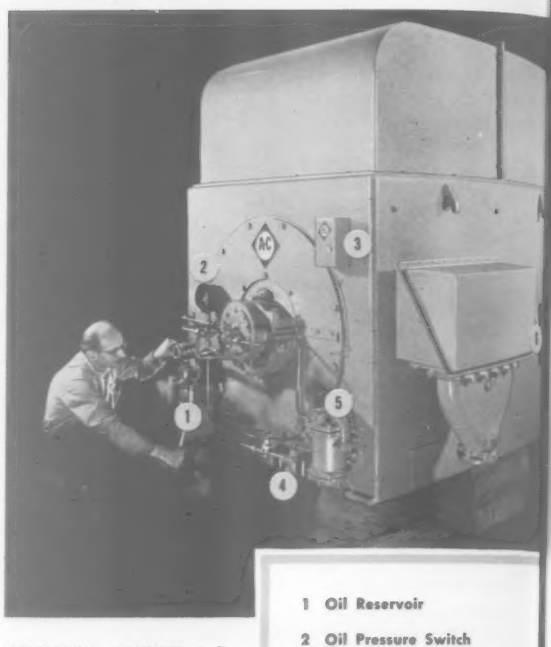
A very similar or alternate type of detector commonly used on smaller machine bearings is the thermocouple. In this case, temperature measurement depends on the fact that in a closed circuit containing two dissimilar metals, a voltage develops which is a measure of the temperature difference between the two junctions of the metals. One, the measuring junction, is located at the point where temperature is to be measured. The other, the reference junction, is either kept at or compensated to a fixed temperature. Leads are brought out from the thermocouple to a conduit fitting for connection to the control instrument.

The temperature measuring instrument used with thermocouple detectors must be of the potentiometer type. Like the Wheatstone bridge, it can be arranged with a selector switch to indicate a number of temperatures at different locations, or automatically record those same temperatures. It can also operate audible or visual alarm devices. Both the resistance and thermocouple arrangements can be made to trip the motor control circuit with suitable relaying. The indicating instrument or alarm device is mounted by the control or switchboard manufacturer.

The babbitted sleeve bearing is reliable if the proper amount of good quality oil is maintained and the lubrication system is functioning properly. The motor shaft runs on a film of oil with no metal-to-metal contact, thereby eliminating wear. For horizontal motors below 3000 rpm, self-ring-oiling is employed. The bearing is lubricated by means of revolving rings that carry the oil from the bearing oil reservoir to the actual bearing parts. However, two-pole motors in the larger ratings are forced-oil lubricated. To maintain this pressure lubrication, an oil pressure switch with alarm contacts can be mounted in the piping system to give notice of pressure failure that may be corrected before bearing damage can result. Forced-oil lubricated bearings are also equipped with ring oiling that will maintain operation for a short time after pressure lubrication fails.

Variety of protective devices available

Figure 7 shows the various protection methods used on a single 1500-hp, totally-enclosed motor with air-to-water heat exchanger. In addition to the main lead terminal box, with pothead, the motor has a conduit fitting (1) for space heater leads, and a terminal box (2) for stator temperature detector leads. Dial thermometers to indicate air temperatures in and out of the heat exchanger will be added at (3) when the motor is installed at its operating site. On the opposite side of the motor, the neutral leads are brought out to three current transformers enclosed in a large terminal box.



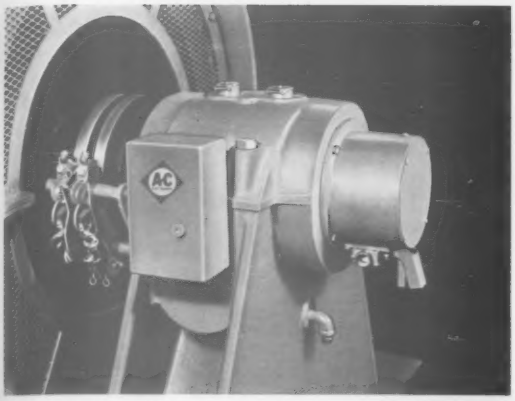
PROTECTIVE DEVICES indicated provide maximum protection for this totally-enclosed 1500-hp, 3580-rpm induction motor. Additional devices, not shown, include current transformers, dial thermometers to show air temperatures in and out of coolers, and a water-flow meter set in feed line to cooler. **(FIGURE 7)**

1 Oil Reservoir
2 Oil Pressure Switch
3 Bearing Temperature Relay
4 Twin Oil Filters
5 Oil Cooler
6 Space Heater Conduit
7 Terminal Box for Stator Temperature Detector Leads

The bearing forced-lubrication system is mounted on the front end of the motor, with a gear type pump direct-connected to the motor shaft. An oil pressure switch (4) is mounted on the pipe line to the bearing. The oil cooler (5), twin filters (6), and reservoir with oil-level sight gauge (7) are located below. The bearing temperature relay for the front bearing is mounted in a rectangular metal case (8), and a relay for the rear bearing is mounted in like fashion on the opposite end.

Also mounted on the coupling end of the motor are pipe connections for the cooling water supply. A water flowmeter with alarm contacts will be installed in the feed line. Provision has been made to drain the water from the air cooler if that should become necessary.

Protective measures other than instrumentation can further minimize bearing troubles. Circulating shaft cur-



SPEED LIMIT DEVICES are particularly recommended for motor-generator sets or where it is necessary to protect equipment against damage resulting from overspeed after loss of dc field. **(FIGURE 8)**

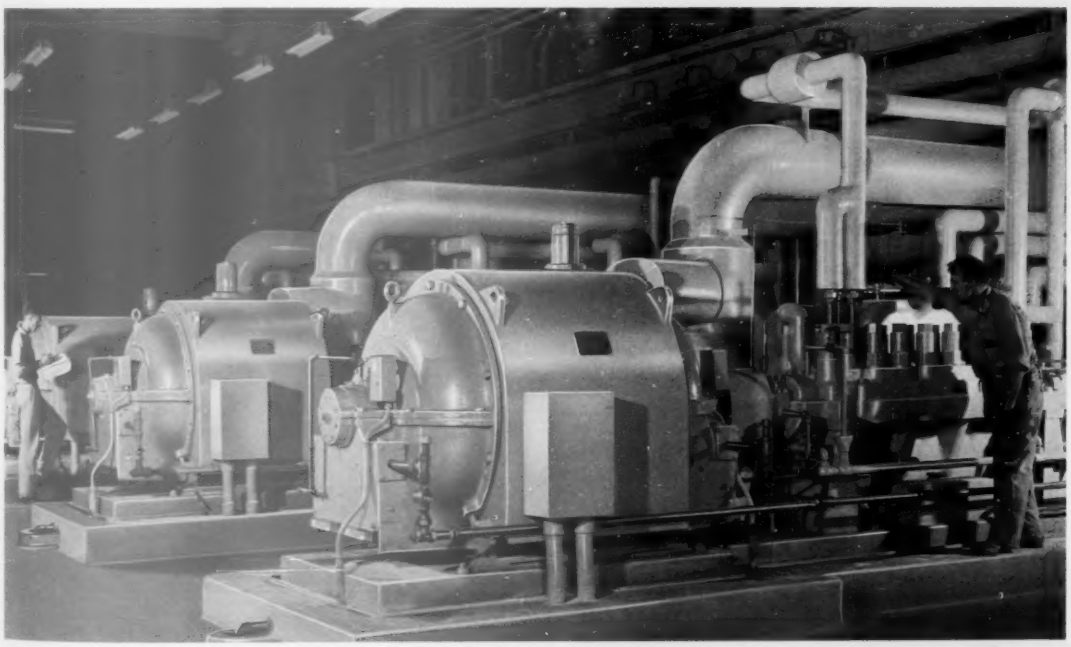
rents can cause bearing deterioration, pitting bearing surfaces and breaking down the oil film between the shaft journal and the bearing bushing. Good motor design gives adequate protection against circulation of shaft currents by placing insulation between the yoke and bearing bracket, between the bearing bracket and bushing, or under one or both bearing pedestals. Operating engineers should make sure that insulation is not shorted by painting or covering with any conducting substance, and that insulating surfaces are kept clean and dry.

It may also be necessary to protect motor bearings against trouble resulting from end thrust on drives with unlimited end-float couplings. Motor bearings are normally not designed to take thrust from the driven machine. Limiting coupling float where standard motors are driving centrifugal pumps, fans, blowers, etc., is the most practical solution.

Speed limit switch protects m-g sets

A speed limit switch, shown in Figure 8, is standard equipment on large motor-generator sets. It is a protective device against damage from overspeed which may result after loss of dc field. Overspeed protection should be applied on any machine coupled to another machine that, in turn, could drive the combined unit at dangerous overspeeds during an abnormal operating condition. The mechanical overspeed device operates on the principle of centrifugal force and is mounted on the outboard end of the motor shaft. It has normally closed or normally open contacts that should be arranged to trip the motor circuit breaker. In the case of dc motor-generator sets, the contacts should be arranged to trip the dc generator breaker also.

Most of these accessories are not furnished as standard equipment but are available with the motor at the option of the purchaser. Where motor shutdowns can mean a loss of vitally needed production capacity, or of a major central station auxiliary, protective precautions can provide an extra margin of safety, and the additional investment is cheap insurance against costly breakdowns. These devices can give an indication of faulty operation, and allow remedial steps to be taken before more serious trouble can develop.



POWER STATIONS and other installations where machines are arranged in groups prefer a centralized method of bearing temperature indication. Dangerous bearing temperatures on these 2000-hp, 3580-rpm cage motors at a power plant are indicated at one control center.

ANALOGIES and ENERGIES

by D. JOURNEAUX
Patent Attorney
Allis-Chalmers Mfg. Co.

Energy, without which life and matter could not exist, makes things behave like mathematical entities.

PART ONE OF TWO PARTS*

MACHINES HAVE GRADUALLY relieved man of much of the physical labor he used to perform himself. In addition, they now do as much work as countless men and beasts that the earth could not even support, so that we may be fed, clothed, housed, and entertained.

But machinery, like beasts of burden, must be ordered about. This in itself has become a tremendous task. That is why machinery itself now often takes over from man the observation and evaluation of machine performance, followed by formulation, transmission and enforcement of orders. Those control functions involve many devices, such as regulators, servomechanisms, and amplifiers, which use mechanical, electrical, hydraulic or pneumatic energy, and often use more than one kind of energy.

Naturally, it is desirable to know beforehand how a contemplated control system will operate, but the analysis of even relatively simple systems under transient conditions often leads to unmanageable mathematics.

* PART II explains in detail how the equations, representing the operation of the various systems shown in PART I are obtained from the balance of energies. PART II also gives the step-by-step solution of the general second order equation to obtain the value of the transient component. Get reprint of both parts free, by filling out and returning this issue's post card insert, or by writing to the editor.

Analogous systems aid progress

Fortunately, systems of many types are analogous in that they obey the same mathematical equation. This is obtained, for example, if they involve the same combination of means for converting, storing and dissipating energy and operate under similar boundary conditions. A system difficult to build or to analyze may generally be simulated by an analogous system utilizing a different form of energy, which may be easy to build and to observe.

When a system containing energy storage devices passes from one state to another, the amounts of energy stored at the beginning and at the end of an infinitesimal time interval differ to an extent depending upon the nature, connections and dimensions of the elements of the system. It is to be expected, therefore, that the transient operation of energy storage systems can be represented by differential equations.

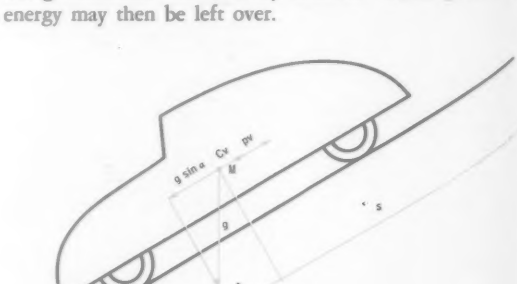
The more energy storage devices there are in the system, the higher the degree of the equation and the greater the difficulty of solving it. For that reason, at least preliminary computations are often made neglecting all but one or two energy storage devices. If this is done with discretion, sufficiently accurate results may be obtained.

First order systems

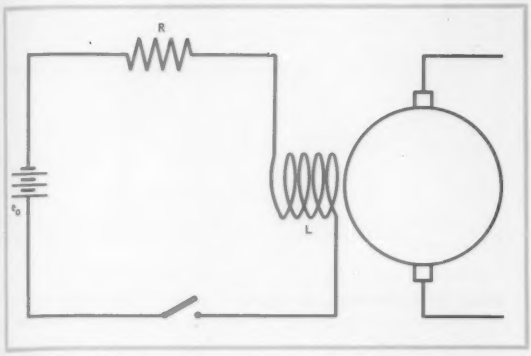
The simplest systems, and those which are most drastically simplified, may lead to a linear differential equation of the first order.

Consider, for example, the thoroughly degadgetized automobile of mass M shown in Figure 1. Assume the car to coast from standstill down an incline forming an angle α with a horizontal plane. Assume further, twisting the facts a little, that the friction of the car is entirely of the viscous type, and dissipates energy at the rate of MCv^2 proportional to the square of the speed of v of the car.

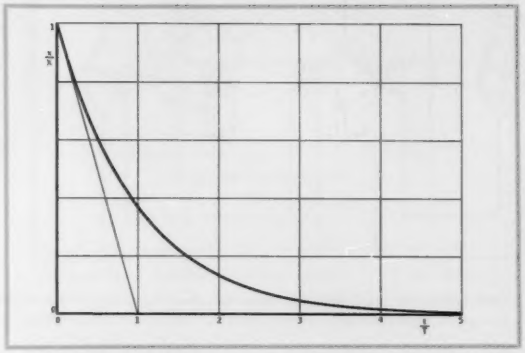
Potential energy was stored in the car when it was driven all the way up the length l of the incline against the acceleration g of gravity. When the car has rolled down a certain distance s, a part of this potential energy has been converted into kinetic energy. Another part is being converted into heat by friction. Some potential energy may then be left over.



VEHICLE COASTING down a straight incline, as shown above, converts potential energy into kinetic energy and heat. **(FIGURE 1)**



CHEMICAL ENERGY in this instance is the source that supplies magnetic energy to the field of this generator. **(FIGURE 2)**



DIMENSIONLESS CURVE of the transient component characteristic of the car of Figure 1 and the circuit of Figure 2. **(FIGURE 3)**

The law of conservation of energy requires a continual balance of this energy budget. Neglecting the rotation of the wheels, the equation of motion of the car may be written

$$pv + Cv = g \sin \alpha \tag{1}$$

in which p is the differential operator.

We may find an analogous system in the generator field circuit of Figure 2, which has a total resistance R and an inductance L. When the switch is closed, the source of excitation voltage e_o converts mechanical or chemical energy into electrical energy. A part of this energy is stored as magnetic energy in the magnetic field, and the rest is converted into heat. The energy balance gives the voltage relation

$$L\,pi + Ri = e_o \tag{2}$$

Equations (1) and (2) may be reduced to the general form

$$px + \frac{1}{T}x = f(t) \tag{3}$$

in which f(t) is called the forcing function and T is called the time constant. The forcing function may be a function of time t but may also be a constant as in equations (1) and (2).

The complete solution of equation (3) is the difference of a steady state component and a transient component. The steady state component results from the presence of the source of energy whose action is represented by the forcing function. It may be obtained without recourse to differential equations.

Transient component lacks energy source

The form of the transient component is independent of the forcing function, but its magnitude depends on the initial value of the steady-state component. The transient component represents the operation which would take place if, the steady-state having been established, the source of energy were suddenly removed. The system, thus left to itself, is in disequilibrium; its fictitious transient operation is dictated by the characteristics of its elements and by its condition when it was cut loose from the source.

The steady-state and transient components momentarily cancel each other when the source of energy takes effect. The previously established conditions then gradually begin to change to make way for the prescribed steady state.

If the time constant multiplied by the forcing function equals a constant X, the steady-state component x is also equal to X. In dimensionless form it is equal to unity:

$$\frac{x}{X} = 1 \tag{4}$$

The logarithmic transient component, also in dimensionless form, then is

$$\frac{x}{X} = \epsilon^{\frac{-t}{T}} \tag{5}$$

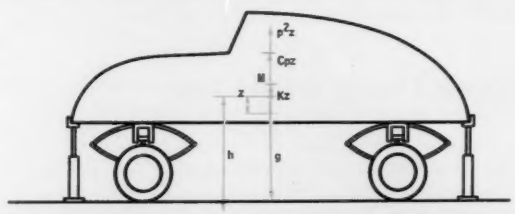
Its time variations may be represented by a single dimensionless exponential curve, Figure 3, in which t/T is taken as abscissas and x/X as ordinates. The initial magnitude of the transient component is unity, and its initial rate of change is

$$\left(p\frac{x}{X}\right)_o = -\frac{1}{T} \tag{6}$$

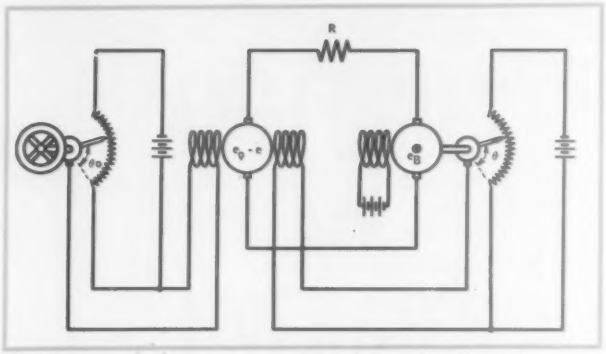
If this initial rate of change were maintained, the transient component would end when t/T is equal to unity. Actually, at that time the transient component still has the value $1/\epsilon$ or 0.367. When t/T is equal to four, the transient component has decayed to less than 0.02 and may usually be neglected from there on.

Second order systems

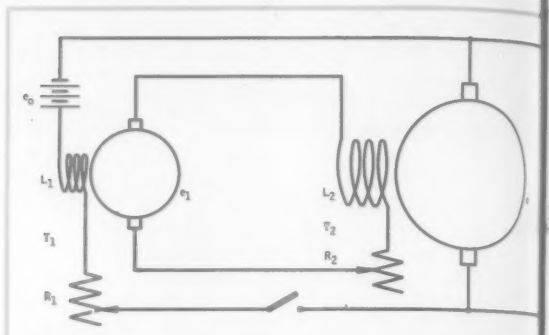
Some more complicated systems lead to linear equations of the second order, which are still manageable. Integration may then yield solutions representing different basic types of transient operation. A particular system may be capable of only one type, or it may go over from one type to another when the dimensions of its elements are varied.



DURING BOUNCING a part of the potential energy of an automobile is stored in the springs. Part is converted into heat. **(FIGURE 4)**



THIS REMOTE POSITIONER may be unmanageable if too much energy is stored in the rotating parts of the receiver. **(FIGURE 5)**



SPEED OF RESPONSE and "overshoot" of this regulator vary together when the energy storage capacity of fields is changed. **(FIGURE 6)**

Besides the usual steady-state component, the solution of a second order equation may have a transient component consisting of two decaying exponential terms. This represents a more or less damped non-oscillatory operation resulting from dissipation of energy in the form of heat at a relatively high rate. Such an operation may be desired in some devices, such as door closers, but may be too slow for others.

More frequently the operation is of a mixed logarithmic and oscillatory character, where the exponential factor decreases in time, and a damped oscillatory transient component is obtained. Even though it causes a so-called overshoot at the beginning, this type of transient is often desirable because it is faster than purely logarithmic transients which dissipate energy at a higher rate.

The transition between oscillatory operation and non-oscillatory operation is the critically damped operation, in which the transient component involves a single exponential factor.

Five analogous systems capable of those different types of operations are illustrated. Figure 4 shows the automobile of Figure 1 on level ground. Assume that potential energy was stored in the body by jacking it up to a height h just sufficient to relieve all four suspension springs. What happens if the jacks are kicked away simultaneously?

When the body has dropped a certain height z, a corresponding amount of its potential energy has been converted to some other form as when the car rolled downhill. Here, however, the conversion of energy into heat takes place largely in the shock absorbers, and some energy is stored in the suspension springs as potential energy.

Again an energy budget must be established. If enough simplifying assumptions are made the resulting equation of motion of the bouncing automobile body, expressed in terms of accelerations, may be in the form:

$$(7) \qquad p^2z + Cpz + Kz = g$$

Electrical energy changes form

Figure 5 shows a positioning servomechanism comprising a potentiometer transmitter. The latter presets the excitation of a direct-current generator having field windings of negligible inductance. The generator supplies the armature winding of a follow-up motor, the loop formed by the two armatures also having a negligible inductance.

The motor actuates a second potentiometer which excites a balancing field of the generator. The motor armature and its load have appreciable inertia but dissipate a negligible amount of energy by friction and windage.

When the transmitter is moved, the generator is excited and converts mechanical energy (supplied by a prime mover) into electrical energy. A part of this energy is converted into heat in the resistance R of the armature loop. Another part accelerates the motor and is stored as kinetic energy in the motor armature and in the load. The equation of motion of the motor armature is

$$(8) \qquad p^2\theta + \frac{b^2}{IR}p\theta + \frac{K}{I}\theta = \frac{K}{I}\theta_o$$

In the regulating system of Figure 6, a direct-current generator bucks a reference battery of voltage e_o in the field circuit of its exciter. Electrical energy is supplied to the field circuit of the exciter at the expense of chemical energy stored in the battery, and to the field circuit of the generator at the expense of mechanical energy supplied by the prime mover driving the exciter.

During steady-state operation this electrical energy is converted into heat at the rate at which it is produced. During transients some electrical energy is converted into magnetic energy or vice versa to vary the amounts of energy stored in the magnetic fields of the machines, and some still goes to heat. The variations of the generator voltage e are given by

$$(9) \qquad p^2e + \left(\frac{1}{T_1} + \frac{1}{T_2}\right)pe + \frac{A_1A_2 + 1}{T_1T_2}e = \frac{A_1A_2}{T_1T_2}e_o$$

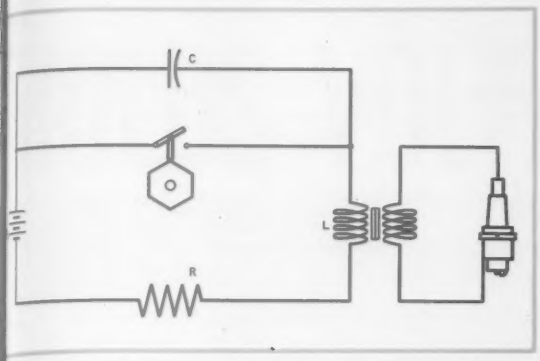
The primary circuit of an automobile ignition system, comprising a coil and a circuit breaker shunted by a capacitor, is shown in Figure 7. When the breaker is closed, chemical energy of a battery of voltage e_o is partly stored in the magnetic circuit of the coil and is partly converted into heat.

When the breaker is opened some energy is also stored in the capacitor. When the capacitor has acquired a charge q, the current in the circuit has the value pq. Here again the law of conservation of energy controls, and if the current in the spark gap may be neglected, leads to

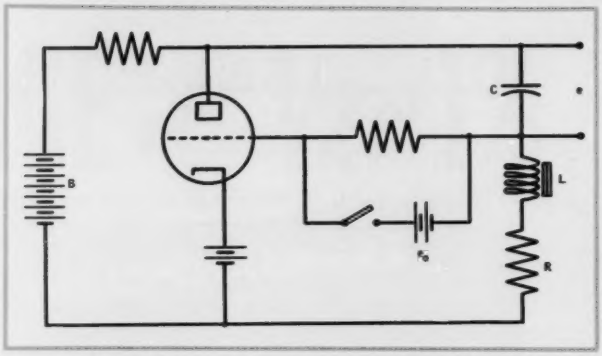
$$(10) \qquad p^2q + \frac{R}{L}pq + \frac{1}{CL}q = \frac{1}{L}e_o$$

Finally, Figure 8 shows a negative feedback amplifier.*

* This example was supplied by W. F. Eagan.



TRANSFER OF STORED energy between capacitor and coil is the basis for the operation of this automobile ignition system. **(FIGURE 7)**



AMPLIFIER SIMULATES other systems by transferring energy between load circuit capacitor and feedback reactor. **(FIGURE 8)**

Chemical energy stored in the B battery is partly converted into heat in the feedback circuit, partly stored as magnetic energy in the output circuit reactor, and partly stored as dielectric energy in the capacitor. The signal component of the output voltage of the unloaded amplifier answers to the approximate relation:

$$(11) \qquad p^2e + \frac{R}{L}pe + \frac{A+1}{CL}e = \frac{A+1}{CL}e_o$$

The amplifier of Figure 8 is analogous to the systems of Figures 4 to 7 in that, with a suitable choice of circuit dimensions, it can assume the mode of operation to be expected of any of them. While any of the five systems can be used as a model for the others, the amplifier is likely to be preferred because of the ease of adjustment of its circuits, which carry small currents.

Damped oscillatory operation

The transient operation of a system in which the transient component is of the logarithmic type usually does not present very serious problems. The parameters of equations (7) to (11) therefore are here assumed so chosen that the transient variations of the unknown quantity are of the damped oscillatory type in each case. The five equations may then be reduced to the general form

$$(12) \qquad p^2x + 2\omega_n \cos\phi \; px + \omega_n{}^2 x = f(t)$$

To put an equation in this form, ω_n is first computed by taking the square root of the coefficient of the unknown quantity x; to obtain cos ϕ the coefficient of px is then divided by $2\omega_n$. The transient component of the solution of equation (12) may be given the following dimensionless form:

$$(13) \qquad \frac{x}{X} = \frac{\epsilon^{-t\omega_n \cos\phi}}{\sin\phi} \sin(\phi + t\omega_n \sin\phi)$$

The solution in this form can be written directly by taking the values of parameters ω_n and ϕ from equation (12). But it is valid only where the first derivative of the unknown quantity has the value of zero at time zero. This is true of the unknown quantities of equations (7) to (11), but not necessarily of other variable quantities involved in the systems of Figures 4 to 8.

Figure 9 shows a family of dimensionless curves of x/X plotted against $t\omega_n$ for different values of cos ϕ. Those curves are sine waves modulated by the exponential damping factor of equation (13). Each curve is contained between a pair of logarithmic curves of equation

$$(14) \qquad \frac{x}{X} = \pm \frac{\epsilon^{-t\omega_n \cos\phi}}{\sin\phi}$$

having ordinates $\pm$ 1/sin ϕ at time zero and a time constant $1/\omega_n \cos\phi$. At time zero the tangents to the curves therefore would make the angle ϕ with the axis of ordinates if the same scale was used on both axes.

The parameter cos ϕ is proportional to the rate at which damping energy is being dissipated as heat at the time when px is equal to unity. When cos ϕ is equal to unity, as it can be, the oscillations vanish and the variation of the x/X is critically damped. If it could be zero, the damping would vanish and the oscillation of x/X would be sinusoidal of angular velocity ω_n. This corresponds to the optimistic assumption that the amount of energy dissipated in the form of heat is negligible.

Damping of system determines value

For any value of ω_n in equation (12) cos ϕ is the ratio of the actual coefficient of px to the coefficient px would have if damping was critical. Cos ϕ, which is sometimes represented by the letter r, or the Greek letter zeta, is therefore called the ratio of actual damping to critical damping, or specific damping coefficient.

Very frequently the practical value of a system hinges on giving it the proper amount of damping. With too much damping the system is too slow, and with too little it is continually in motion. It is therefore useful to determine the effects of varying the ratio cos ϕ.

The natural angular velocity ω of the oscillations of x/X remains constant during the entire transient. It is always lower for damped oscillations than for undamped oscillations and has the value

$$(15) \qquad \omega = \omega_n \sin\phi$$

where ω_n is the undamped angular velocity. The variation of ω/ω_n in function of cos ϕ may therefore be represented by a quarter of a circle as shown in Figure 10.

Returning to Figure 9, the first peak of each curve of x/X occurs at the beginning of the transient at time zero. Its height is unity. The next occurrence of interest in the course of the transient is the first passage of the variable

component through zero. This takes place after a length of time

$$t_1 = \frac{\pi - \phi}{\omega} = \frac{\pi - \phi}{\omega_n \sin \phi} \tag{16}$$

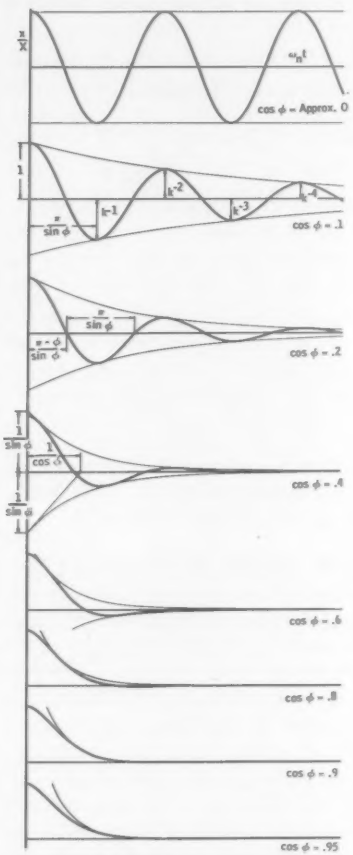
The value of $\omega_n t_1$ in function of cos ϕ is plotted in Figure 11. It may be seen that when damping is decreased the first drop of x/X to zero is accelerated.

Next to occur is the "overshoot," i.e. the second peak at time $\pi/\omega_n \sin \phi$. It follows the first passage of x/X through zero by a time interval $\phi/\omega_n \sin \phi$ which is obviously shorter than time interval t_1. Its value is the reciprocal of the damping factor k:

$$k = \epsilon^{\frac{-1}{\pi} \text{ cotan } \phi} \tag{17}$$

The damping factor k in turn is the constant ratio of the amplitude of any peak to the amplitude of the next one. The overshoot thus is also equal to the constant ratio of the amplitude of any peak to the amplitude of the preceding one. Its value in function of cos ϕ is plotted in Figure 12.

When damping is decreased the overshoot increases. The choice of cos ϕ therefore will depend on the relative merits of a fast response and of a low overshoot, and will represent a compromise unless damping devices are added to the system.



DIMENSIONLESS CURVES of oscillatory transients for different values of damping are shown above. **(FIG. 9)**

Logarithmic decrement

Another quantity of interest is the logarithm of the ratio of amplitudes of any two successive peaks of the same sign. This is called the logarithmic decrement and is equal to

$$\delta = 2\pi \text{ cotan } \phi = 2 \log k \tag{18}$$

Its variation in function of cos ϕ is plotted in Figure 13.

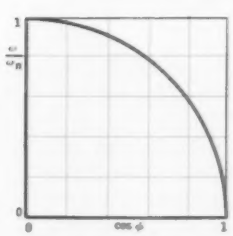
The logarithm of the ratio of amplitudes of two peaks occurring at intervals of unit time is the natural decrement a, which is equal to

$$a = \omega_n \cos \phi \tag{19}$$

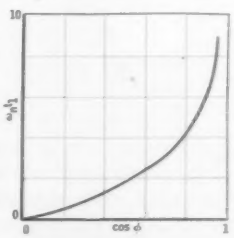
It is therefore directly proportional to cos ϕ and is represented by a straight line in Figure 14.

The different passages of the curves x/X in Figure 9 through zero take place at regular intervals of $\pi/\omega_n \sin \phi$ starting with the first one at time $(\pi - \phi)/\omega_n \sin \phi$. The points at which the curves are tangent to the exponential curves occur midway of those intervals. The peaks of the curves take place at the same intervals but starting from time zero.

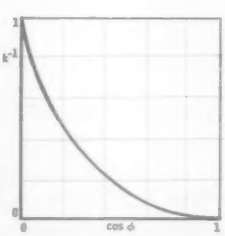
When some of the stored or dissipated energies which were disregarded in the derivation of equations (7) to (11) are not negligible, equations of order above the second are obtained. The solutions of those equations include a steady-state component, and a transient component consisting of several terms. The transient operation of the system may be logarithmic, being the resultant of several variations having different time constants. It may be oscillatory, involving superposed oscillations of different frequencies, and it may have both logarithmic and oscillatory components. The different transient terms however are individually similar to the transients of systems leading to equations of second order.



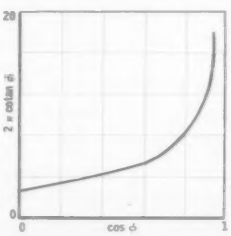
CURVE SHOWS variation of the natural angular velocity of oscillations in function of damping. **(FIGURE 10)**



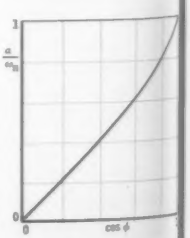
TIME ELAPSED at occurrence of first passage of oscillations through zero in function of damping. **(FIGURE 11)**



"OVERSHOOT" (height of second peak of oscillations) varies in function of damping as shown above. **(FIG. 12)**



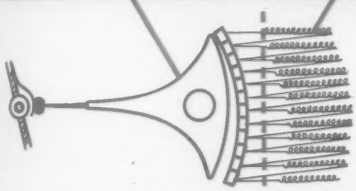
VARIATION of logarithmic decrement of the oscillations in function of damping is illustrated above. **(FIG. 13)**



NATURAL DECREMENT the oscillations in a unit time varies as shown in function of damping. **(FIG.**

HOLDS VOLTAGE within ½ of 1%

ALLIS-CHALMERS
ROCKING CONTACT
Generator Voltage Regulator
POWER PLANT CONTROL



Sealed, dust-tight front portion of regulator housing contains *Rocking Contact* sector pivoted in jeweled bearings. The smooth working, hard graphite sector face rocks on a curved silver surfaced commutator . . . regulates with slight movement . . . reduces wear.

Ventilated rear section contains resistance elements. Each resistance element is wire wound, accurately designed according to the characteristics of your generating equipment. They are connected to the commutator segments within the dust-tight front section.

YEAR AFTER YEAR, regardless of line or load disturbances, proper voltage is accurately maintained. This is the kind of performance you can expect from *Rocking Contact* Voltage Regulators . . . it is the kind of performance users are getting!

"Regulation is tops!" says one user. "Put in service ten years ago and still no sign of needed maintenance," says another. "Not one penny for maintenance in fifteen years of continuous service," says still another.

And there is a reason for this trouble-free performance. *Rocking Contact* Voltage Regulators are precision built . . . require no delicate adjustments. *Rocking Contact* sectors are supported in jeweled bearings, rock on carefully machined commutator segments heavily plated with silver. Just a slight *rocking* motion regulates voltage by varying resistance in the exciter shunt field circuit. Response is fast . . . regulation accurate to within ½ of 1%.

Rocking Contact Regulators stay accurate . . . operate for years without repair or maintenance. Call your nearby A-C representative or write Allis-Chalmers, Milwaukee 1, Wisconsin for more information.

A-3269

Rocking Contact, Regulex and Synchro-Operator are Allis-Chalmers trademarks.

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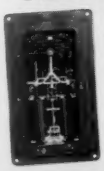
ROTATING GENERATOR VOLTAGE REGULATOR

REGULEX Generator Voltage Regulators are recommended for use with large generators where field forcing and extremely fast response are required. High amplification of small changes produces immediate, strong corrective action. Similar to a dc generator in construction, it has nothing to get out of adjustment . . . replaces pilot exciter.

AUTOMATIC SYNCHRONIZER FOR ROTATING MACHINERY

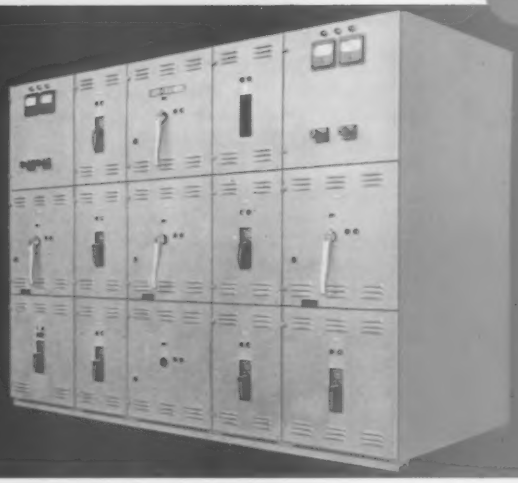


The SYNCHRO-OPERATOR automatically brings the speed of synchronous condensers, alternators and frequency changers to synchronism. While doing so, it indicates relative speed, which machine is faster, phase angle between machines, and the exact point of synchronism. Breaker is automatically closed at the exact point of synchronism. Send for leaflet 14S63868.

HIGH-VOLTAGE SWITCHGEAR FEATURES

- New—less floor space but more room for instruments, relays, transformers, buses, etc.
- Welded-in floor plates simplify foundation requirements, provide easy breaker handling.
- Wide guide rails in breaker compartments add rigidity and protect wiring.
- Looped wiring minimizes wear at points where flexing occurs.
- Horizontal contact separation of *Ruptair* circuit breakers adds thermal assist to magnetic arc interruption.

ALLIS-CHALMERS
Switchgear



LOW-VOLTAGE SWITCHGEAR FEATURES

- Safe dead-front, compartmentalized construction, with entire structure grounded.
- Rigid construction of framework assured by jig-welding and lap joints.
- Breakers of same rating are interchangeable. Pantograph mounting makes circuit breaker withdrawal easy.
- Circuit breakers can be tested within switchgear unit for added convenience.
- Individual, enclosed, wall-mounted breakers available for locations where needed.

Here's *Insurance* for CONTINUOUS PRODUCTION

YOUR accountants can tell you exactly how much your plant and equipment is worth. But productive use of that investment is becoming increasingly dependent on electrical power, and modern switchgear is essential to the efficient, continuous distribution of that power within your plant.

Allis-Chalmers switchgear can help you maintain full production . . . on schedule. Since this equipment is standardized, new units can readily be incorporated if your requirements change during the years ahead. Servicing is cut to a minimum and is quick, easy and safe because design features and engineering details are dictated by operating and maintenance experience.

Some of the features are listed above. More details are given in Bulletin 18B6185. Why not ask your A-C representative for a copy, or write to Allis-Chalmers, Milwaukee 1, Wisconsin. A-3523

Ruptair is an Allis-Chalmers trademark.

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FIRST IN THE U. S. WITH METAL-CLAD SWITCHGEAR